ILLUSTRATIONS OF THE EARTH'S SURFACE

GLACIERS

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PREFACE.

THIS work was originally designed merely to furnish a collection of photographs of glaciers, along with descriptions that might serve to call the attention of the student to the most noteworthy features in the objects represented. When it came to be carried out, this plan was found to have certain defects. It was impossible to give the reader any connected idea of glacial phenomena, or of the importance of ice action in the history of the earth, without supplementing these descriptions of the plates by some connected sketch of the more important parts of the subject matter. To meet the agreement with the publishers, it was necessary to prepare this sketch with far greater haste than was proper in such work. If the reader will consider that the main object in the book is not to afford a complete history of glaciation, but to present a body of graphic illustrations of glacial phenomena, and that the text is designedly subordinate to this purpose, he will then better understand the apparent shortcomings of the work.

It is not amiss to give some of the more important reasons that have led to the preparation of the series of Illustrations of the Earth's Surface, of which this volume constitutes the first part. A long experience in teaching geology has convinced the authors that the greatest

difficulties in such instruction are those which arise from the remoteness of the facts on which the teaching must rest. The professional geologist may meet these difficulties by means of travel; but the teacher must contrive to bring to his students some means of vivifying their conceptions more effective than any words can be. The delineations of nature in our text-books, even in the important monographs on geology, are necessarily diagrammatic. The photographer's art alone can supply representations of the character required when the object is to give an accurate representation of the facts as they really occur.

The plan of these Illustrations of the Earth's Surface contemplates a series of volumes, severally entitled Glaciers, Mountains, Volcanoes and Earthquakes, Lakes and Plains, Rivers and Valleys, the Sea and its Shores, Structure of Rocks, and the Effects of Life. Where practicable, the illustrations will be reproduced from photographs; when it is necessary to depart from this plan, every care will be taken to insure the utmost fidelity to nature in the delineation. As far as possible diagrams will be used only to show the features that are capable of illustration in this way alone. The text will be so arranged as to give a connected idea of the more essential facts and theories that belong to each subject. Each of these volumes will be as independent of the others as it is possible to have it; the only connection being in the plan that underlies the whole.

In this volume the text was written by the senior author, who is also responsible for the plan of the whole work; the diagrams and bibliography were prepared, and the plates selected and described, by the junior. It is proper to state that some of the views advocated in the text are rather those of the writer than of his collaborator.

It is hoped that the list of works upon glacial subjects, which is given at the end of the book, may serve to guide the student to many of the details of this important branch of geology, which are necessarily omitted in this general sketch of the matter.

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GLACIERS.

CHAPTER I.

INTRODUCTION.

THE student of the earth's structure should at the outset endeavor to possess himself of some general ideas concerning the part played by water in its physical life; all the machinery of our earth is so far determined in its action by the work of water that we may say that our planet could not have had the least likeness to its present self were it not for the properties of this fluid.

Perhaps the best way to set before ourselves a general outline of the work of water is to compare the condition of the surface of the moon with that of the earth. With a favorable atmosphere our modern telescopes permit us to inspect the surface of the moon in a very perfect way, so that we know the character of the part that is turned towards us better than that of any of the earth's land areas except Europe. Watching his chances, the student may, by means of his telescope, in effect transport himself to a point about one hundred miles above the surface of the moon, where he can see its fields more clearly than he beholds the face of the Alps from the neighboring mountains of the Jura. With care and patience he may unravel the structure of the wonderful surface below him, until every important feature is clear, and he is able to see in just what respects it differs from the earth. This search shows him a world utterly different from that which he inhabits. The continents and the seas of the earth have nothing like them in the moon. Our mountain chains and their valleys, leading with continuous slopes from the highlands to the ocean basins, are wanting there. The

whole surface is thickly sown with pits resembling our volcanoes. These pits vary in size from great basins several hundred miles in diameter to craters so small that the telescope can just discern their existence. Some are so large that all New England could be placed on their floors, and others so small that they could be covered by the Boston State House. Wherever we look we see an indescribable desolation, a state of death to which our most desert earthly places offer no likeness. The surface of this dead sphere is stirred by none of those motions that give the physical life of our earth: it is silent, save when, at rare intervals, the sun's heat, expanding the rocks during the long lunar day, impels some fragments down the steeps of the volcanic craters. In a word, we have here a world left as it was when the ancient internal forces of its sphere died into inactivity.

This lifeless and desolate world gives us an idea of what our own earth would have been if water had been denied to it. Even if the atmosphere had been able to maintain itself without the presence of the seas, there can be no doubt that, when the original fires of the interior had burned low, the surface would have fallen into the shape we now find on the moon, and that this desolation would have been prolonged until the next part in the history of our solar system brings an utter change in all its machinery.

The admirable work of water on the earth's surface is accomplished by virtue of certain very peculiar properties, — properties that separate it very widely from every other substance that exists in the universe, all of which are essential to its work. In the first place, water is a substance capable of assuming the three forms of solid, liquid, and gas, within the narrow range of temperature proper to the earth's surface. In the second place, it has a greater capacity for heat than any other substance; that is, it is capable of freighting itself with a very large store of that form of force we call heat, and conveying it by its motions to great distances. Thirdly, it has a peculiar power of dissolving almost all other substances that compose the earth. To these powers, which are here but inadequately stated, we owe the machinery of the earth's surface and its wide difference from that of the moon.

All the force that makes that machinery operate comes to the earth in almost equal share from the remote fixed stars and from that nearer source of power, our sun. The greater part of this power flies away again into space, but a part of it is caught up by the water and built into the economy of the earth, making the vast fabric of organic and inorganic life. Every breath that is drawn, every pulse that beats, the power of the sap that climbs in the plant, the rivers, the rains,

the currents of the sea, even the winds, are one and all but manifestations of the celestial force made possible only through the powers of water.

It is an often stated fact that water accomplishes its circuit from the seas to the clouds, from them to the rivers, and thence back to the sea, through the action of the solar forces; but to have a proper conception of the phenomena of the water circulation of our earth, we must bear in mind the fact that each molecule of water owes its elevation into the clouds not alone to the action of the sun, but that every star that shines takes part in the work. In the formation of each rain-drop every sun in space has a share; without the help of this unseen heat from the stars the sun would be powerless to melt even the equatorial seas.

It is to the water of the atmosphere also that we owe the capacity of the air to retain the heat that is required to make the earth the seat of organic and inorganic life. But for the small amount of vapor always in the atmosphere this heat would slip away as fast as it is received, and each summer night would bring down to the earth the intense cold of the outer spaces. Less than ten miles above the earth's surface, almost within cannon-shot distance, the air never rises above the freezing-point, and only a hundred miles or so away the space beyond us is at a temperature at least two hundred degrees below zero of Fahrenheit. It is practically the water in the air, which, acting as a blanket about the earth, fends off this eternal cold of the celestial spaces, and makes the earth an oasis of life and warmth in their great waste of lifelessness. Although the air, by virtue of its water, is enabled pretty effectively to retain the share of heat necessary to the life of the earth, it is a very close battle. The uppermost of our clouds, though they are not over about eight miles from the earth's surface, are frozen; their water being in the shape of minute bits of snow or ice. Every winter, when the sun's power is diminished, this region of cold creeps nearer the earth, and in high latitudes gains a temporary empire even at sea-level. Wherever mountains elevate themselves to great heights, even in equatorial regions, they come far enough into this region of outer cold to get beyond the zone of life.

To this frequent gain of the outer cold on the low-lying warm zone of the earth we owe the fact that water takes on the shapes of ice and snow,—shapes in which it for a time loses its character of a life-giving element and becomes the very pall of death. To this temporary and limited control that the outer cold acquires over water we owe the peculiar phenomena of glaciers, and indeed all of the work of frost and ice; whenever the outer spaces prevail over the warmth that

the blanket of moist air holds about the earth, water passes from the fluid to the solid state, and the earth's surface begins to take on the aspects of physical and organic death. In the marvellously well-balanced conditions of the earth's surface this congelation of water, though always occurring, has never been universal, has indeed never become so general as to break the long succession of life that leads up from the remotest past of the earth's history. As we shall see hereafter, during the hundred million or so of years, the imperfect record of which appears in our stratified rocks, we have evidences that life has been continuously present, so that we are justified in believing that it has done its peculiar work ever since the dawn of geological history: and the same record shows us that at no time has the cold of our earth's surface been so great as to convert all of its water into the state of ice; for had this ever happened the present system of organic forms would have been destroyed, and the series of organic beings, if it ever reappeared, must have begun again with the lowest forms.

To see the peculiar delicacy of this adjustment of the temperature conditions which have prevailed since the beginning of the organic record, we must consider the immense range in the temperature that we find in the part of the universe near about us. Limiting our view to the narrow bounds of the space that lies between the centre of the earth and the centre of the sun, we find that in the centre of the earth we have a temperature that is to be counted by thousands of degrees, and possibly may reach one hundred thousand degrees Fahrenheit. The surface of the sun cannot have a temperature of less than one hundred thousand degrees, while it may much exceed that amount; at the same time the temperature of the space that lies between the earth and the sun is pretty surely not less than two hundred and fifty degrees below zero of Fahrenheit's scale. Thus we have in the universe about us a range of temperature that is enormous beyond conception. In its great scale the temperature that permits the combinations of water that are the conditions precedent of the existence of organic life occupies but a very small space. If the temperature of the whole earth's surface should ever, for a considerable period of time, rise above one hundred and sixty degrees, or fall below thirty-two degrees Fahrenheit, that is to say, should it range as much as one hundred and twenty-eight degrees Fahrenheit, the possibility of life would cease on account of the peculiar conditions that water places upon it. On the whole scale of temperatures of our solar system this range is but a narrow span. To conceive its scanty limits, take a line one hundred feet in length as a measure of

the total range of heat in the solar system, mark off on it a space of a little over an inch, and this narrow space will represent the possible limits in which organic life, such as exists on the earth, can maintain its existence. There can be no doubt that the narrow limit placed upon the range of terrestrial temperatures is due to the peculiar powers that belong to water. By its great capacity for heat, and by its peculiar power of resisting radiation when suspended in the atmosphere in the form of vapor, it has been able, in a good degree, to protect the earth's surface from the effects of such changes of temperature as changes of the solar system or other accidents may have tended to bring upon it.

That there have been such accidents the record of the successive ice periods to which the earth has been subjected is sufficient proof. Again and again have the continents been covered by ice sheets such as now only occupy a small space of lowlands about the pole and the uppermost levels of the higher mountains.

For the student of the earth's structure and history this work of ice has the highest interest. In the first place he finds in it an explanation of many of the most interesting features that the earth's surface exhibits. It is only through its action that he can account for the shape of a large part of its surface, or the history of a large part of the deposits that form its crust. In the history of organic life he constantly needs an understanding of the same agent. Many of the facts connected with the migrations and changes of this life are to be accounted for in no other way; even the early development of man was greatly influenced by glacial action. Of all the elements of our understanding of the past the knowledge of these changes of condition in the earth brought about by glaciers is clearly the most important.

The knowledge of this work of glaciers is of all the triumphs of geology the most especially the result of the labor of the last forty years. As might be expected in the case of a branch of inquiry which is so new, much remains to be explained; yet that which is known is large in amount, and is well affirmed. Concerning the active causes of glacial motion, our information, though assuredly incomplete, has gone as far as in almost any of the older lines of research into the action of terrestrial forces. The reality of the former extension of the glaciers during the geological period which came just before our own day is perfectly well ascertained, and we may say the same of the evidence of glacial periods at several stages of the earth's history, while there is enough in our study concerning the physical conditions of glaciers that has already passed beyond the stage of

hypothesis and into the domain of established fact to afford confidence to the student, — a confidence which is likely to be wanting in certain branches of geology. But more still remains in the field the glacialists are searching, a vast field for discovery and experiment. The question of the cause and climate of glacial periods, the nature of the extension of the ice during the last period and those that have preceded it, the nature and causes of the motion in continental glaciers, their effect upon life, — all these lines of inquiry promise to be fruitful of discoveries which will serve to throw a great deal of light upon the history of the earth's surface.

In endeavoring to set before the student the phenomena of glaciers, it will be best to begin by a general inquiry into the nature of the phenomena exhibited in our existing glaciers as they appear in any of the characteristic ice-rivers of the Alps, which have become classical from the studies of the many distinguished naturalists that have worked upon them; with the facts before him it will be well to pursue the steps of those who have found the true ways into the history and mechanism of glaciers, that he may see how the riddles that beset them have been unravelled. The student of nature will find that the best way into any science is through the history of the discoveries that have made it a science. By following the footsteps of those who have found their way to the truth, we pursue natural, if seemingly vagrant, paths. The difficulties of discovery that the pioneers of the science met are the difficulties of understanding that the student encounters. Moreover, there is a human interest about these struggles of man with the problems of the world that adds much to the hard facts of a science, and gives one of the needed graces to the stern features of any physical inquiry.

After having found our way in this fashion into the problems of glacial structure and motion, it will be necessary to extend our studies to the conditions of glaciation which are no longer in existence on the earth's surface. This inquiry is so extensive that we can only glance at the questions which it brings before us; it is the largest and least explored field in geology, but in it the paths of investigation are not yet well determined.

Lastly, we shall be led to consider the relations of glaciation to the life of the earth. Our naturalists are at the threshold of the vast problems that lie in this department of geology. Now and then, however, we can see something of the effects that arise from the driving to and fro of organisms as the continents yield up their surfaces to the conditions of death the ice brings upon them. Recent dis-

coveries have made it certain that man existed before the last glacial period, and saw all its manifold changes. Knowing that our own kind have endured the singular vicissitudes of the last ice time, and survived the struggles that its accidents brought about, the history of its changes is clad with a human interest that did not belong to them before. And as we are compelled to believe that the time to come is again to bring about a recurrence of these times of ice, and that the probable future of our race on earth must lie over such ages of trial, the phenomena become invested with an interest greater than belongs to any other branch of Geology.

CHAPTER II.

THE EXISTING GLACIERS OF THE EARTH.

A Sketch of Swiss Glaciers. — The Recession of the old Ice Streams. — Ancient Moraines. — Near View of the existing Glaciers. — Ice Grotto. — A Walk up the Glacier. — Phenomena of its Surface. — Passage to the Névé. — Character of the Perpetual Snow. — Differences between Alpine Glaciers and those about the Poles. — Paleochrystic Seas.

THE student who would make the acquaintance of glaciers and glacial action in the best fashion should seek them in the Alps of Switzerland. He will there find abundant exhibitions of their beauty and grandeur, and be able from their work of to-day better to conceive their value in the long work of the world. The Swiss glaciers are by no means the largest or by their nature the most instructive of existing glaciers; on the contrary, they present us with conditions so extremely unlike the glaciers that have done the great work of ice on the earth's surface elsewhere and in other ages that the student necessarily receives many purely local impressions from them; but this is more than compensated for by the fact that the Swiss glaciers have been made the objects of nearly all the important observations that have been directed to this subject. A host of able and untiring investigators from almost every country in Europe have devoted themselves to inquiries concerning the laws of glacial action on this field, and the intelligent student will find their labors of value to him at every step of his journey.

Perhaps the best course for the student is to enter Switzerland from the west, so that he may pass up the valley of the Rhone, beginning his studious journey near the Lake of Geneva. If he will leave the railway in the Jura, and cross the strong arches of its fine simple mountains on foot, he will thereby get the best introduction to the Alps. Between the Jura and the main Alps lies the broad

valley of Switzerland, one of those regions of little disturbed table-land which mountain systems often leave between their separate yet adjacent regions of disturbance. Looking from the heights of the Jura, we see this great plain stretching away to the black, wall-like front of the Alps. On this plain lie the beautiful waters of Lakes Geneva, Neuchâtel, and Morat. On the far-away inner Alps that rise in spectral beauty above the sombre outer wall of the mountains, we see the mantle of eternal snow, the shrunken remnant of the old ice sheet that in the geological yesterday overspread all this vista that is before our eyes. The valley before the observer is over fifty miles wide; he stands about five thousand feet above its floor, and the snow-clad hills of the inner Alps rise to nearly thrice that height above the level of the lakes, which have a depth of about twelve hundred feet. Yet in the glacial period this vast trough was filled to a great depth with ice that reached from the crests of the distant snowy mountains to the point where we stand. A simple proof of this lies at our feet: all along the limestone flanks of the Jura, we find masses of ancient crystalline rocks which we know to have come from the sides of those far-away mountains over the slow ferry of the glacier that swept across the valley. The broad glacial stream did not rise above the wall of the Jura, but turned to the southward through the widely opened valley of the Rhone and poured forth its ice until it probably entered the sea, which during this period extended pretty far inland from the present shore.

This glacier of the Rhone evidently held its place for a period of immense duration, measured by human standards of time, though perhaps very brief in terms of geological chronology. While it lay here the lakes upon the plain were dug out by its slow-working engines of erosion, and all the lesser hills and valleys that fret the plain had their shape given them by the same agents.

The recession of the ice from the period of its greatest extension must have been geologically rapid; but the steps of the retreat we follow in passing across the valley of Switzerland and up the tributary valley of the Rhone required a matter of thousands of years for their accomplishment. As we follow the backward march of the ice we find evidence of constant pauses and of occasional readvances. On the plain of Switzerland these evidences require the practised eye to see them, but when we enter the valley of the Rhone we find every few miles proof of these periods of pause and readvance in vast heaps of glacial waste. The arrangement of the pebbles shows these masses to be the terminal moraines or waste-heaps that were formed where a glacier held its front for some time. In

those years when the melting of the glacier went on much more rapidly than it could be fed by ice from above, its terminus retreated rapidly up the valley, and no moraine wall was formed, but stones and sand were strewn evenly along the surface. In the years when a temporary increase of snow pushed the ice stream down the valley more strongly than the sun's heat could beat it back, these heaps of waste we term moraines were formed. They indicate times of arrested retreat, or perhaps occasional gain, when the waste brought down by the slow-moving ice was accumulated at its termination. In its process of retreat it is easy to see that what was the one great glacier of Western Switzerland during the time when the ice period was at its height, became divided again and again as it shrank into the valleys. In the earlier stages of its retreat it separated into the glaciers of the Rhone, the Dranse, etc. Then, as the retreating ice passed up the main valleys of the larger streams, each minor tributary became the seat of an individualized glacier. We may now walk up the Rhone valley, tracing where each of the lateral glaciers left the main stream in its retreat, and yet not see a sign of existing ice streams until we come to the glacier of the Rhone at the very head of the valley. If, however, we turn into any of the stern gorges whose gates open into the more smiling main valley, and ascend the steep beds of their streams, we soon find ourselves as high above the sea as ten times the same distance further up the slope of the main valley would have lifted us. We find that the mountain torrent has the sources of its yellow waters in a low arch in the ice wall at the foot of the glacier. Wherever the tributary stream has its waters turbid with fine mud, we may know its source is in the glaciers, for the waters that emerge from beneath them are always yellow with finely ground stone. When the stream runs pure, transparent water, we may know that it comes from a valley where the ice no longer lies. This, we may remark in passing, is the best proof of how much more effective as an instrument for wasting the earth's surface is water in the form of ice than in its fluid shape. All the year these ice-fed streams are bearing their burden of waste to the lower levels of the earth, while the streams that drain valleys free from glaciers carry hardly a trace of sediment.

Going farther up the valley of the Rhone, we can see that the footprints of the ice become constantly fresher. Out on the plain of Switzerland, the less resisting pebbles of the moraines are much decayed, and the masses of detached matter are themselves greatly worn by the agents of erosion. As we ascend the

valley it becomes clear that we come nearer to the source of the actions that built these heaps of waste, and that they have not been so long in existence. The pebbles that compose them are less and less affected by decay. The soil that rests upon them becomes thinner; they are no longer forest-clad; and finally, just before we come to the wall of the existing glacier, these great moraines stand as nude in their shape as if they had been made yesterday.

The first near view of a glacier is not usually so impressive as that of most of the other great manifestations of the power of water. The sea-shore, a waterfall, even a mighty river, are all more majestic than the lower part of these ice streams. At first sight it generally appears like a rude heap of stones and dirt across a narrow valley. Above this rude wall of disorganized waste there rises a worn and bedraggled heap of rent and dirty ice. Its face that looks down the valley is steep, and may rise some score of feet above the moraine at its base. This face is deeply furrowed by gullies, down which during warm days flow the rills that have carved them out. Here and there in these furrows we see the deep blue color of the glacier, little patches of beauty in the ugliness of slipping rubbish that is always making its way down to add to the heap at the base. Every few minutes some bits, great or small, start from the pinnacled crest, and gather an avalanche as they rush down the slope to their resting-place at the bottom. If the glacier be large, gathering the drainage of a considerable valley, there will be a stream emerging beneath its terminal wall. A cut made by its waters through the moraine gives us access to the very bottom of the ice, where it rests upon the rock foundations. Here we find the water emerging from a cavern which often penetrates far beneath the surface of the ice. This cave is often of noble proportions, its great arch rounded by the wear of the water and the heat of the air; from time to time, as the widening arch becomes too weak for the weight above, it falls in pieces upon the floor. But the advancing stream of ice soon pushes this waste before it. The stream and air melt it away, and the fresh face of the glacier again gives us its beautiful grotto. If the student is fortunate he may find in these fickle and transitory ice palaces many things that will repay close study. In the first place, he will observe that the stream that emerges from beneath the ice arch is white with sediment. Taking a little of it in a glass, we observe that the greater part of the sediment subsides slowly; it will require some hours for it to become clear. Drawing off the water with a siphon or syringe, we find that we have a layer of sediment composed of a little coarse sand at the bottom, then finer

grains above; but the greater part of the waste is of exceedingly fine-grained material or almost impalpable mud. This silt is what gives to all the streams that come from glaciers their yellow color, and makes the Rhone, the Rhine, and the other Swiss rivers as turbid as the Mississippi in its times of flood. All the great rivers of Europe would lack the blue color, which is their chiefest ornament, and be of this same dun hue, were it not that the ancient glaciers have left many lakes in their paths which serve as settling reservoirs in which this silt is deposited. Since the retreating ice left Lake Geneva open, one third of its length has been filled principally by this waste from under the great walls of the glaciers, and several lakes further up the valley were in succession entirely filled before the process of closing Lake Geneva began. If the cavern extend to some depth into the glacier, we may sometimes observe fissures extending from its arch through to the surface of the glacier, down which pour the little tributaries of the stream below. On the lower part of the walls of the cave we may chance to find a pebble buried in the ice, but with a part of its face firmly pressed upon the rock below, over which it is driven by the slow, onward motion of the ice. Even if such special chances of seeing the structure of the glacier are denied us, there is always a recompense for the time and pains given to their exploration in the wonderful beauty of the crystal walls of the cavern. Without all is begrimed with the mud and stones, but the cave itself is generally very beautiful. When its walls are thin, the transmitted light from without is wonderfully soft; and even when the ice is too thick to admit the light of day, the strong rays from the portal or the light of torches will give a beautiful aspect to the crystalline walls. Nearly all of these characters may be seen in Plates XIII. and XIV.

Before ascending to the upper regions of the ice the observer should mark the evidences of great change in the position of this terminal point of the ice stream. Nothing is more instable than its place. We may find that it has within a year or two shrunk away from the terminal moraine or wall of débris that marks its last halting-place; in this case there is a gap between the terminal moraine and the wall of ice. Plate XV. shows a large barren area uncovered by many years' con-

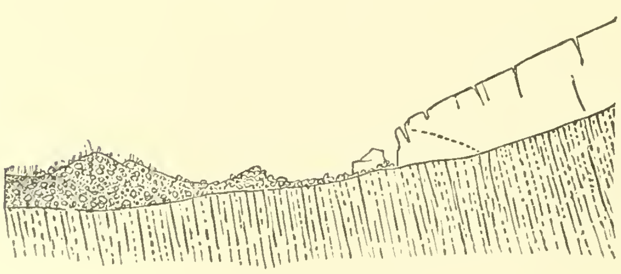


Fig. 1.

Retreat of a Glacier from its Terminal Moraine.

tinuous shrinkage of a glacier. Or, as it now happens with a few Alpine glaciers, the ice stream may be moving its terminus down the valley; when this is the case it pushes along the mass of stones that constitutes the terminal moraine, or turns it aside as easily as the plough turns a furrow. To a great glacier a mass of perhaps a million of tons of boulders is a trifling obstacle. For years a glacier may pursue its course of advance until the conditions become favorable for its retreat, when it again falls back slowly and stubbornly before the force of its enemy, the sun. Sometimes these advances are disastrous to the slender fields of the Alpine valleys through which they are made. Tillage ground is not infrequently destroyed, or the streams dammed until their waters gather lakes of such dimensions that they burst their bonds, and pour as an avalanche of water, ice, and stones through the unhappy valley below.

Taking to the cliffs that bound the valley, for terminal parts of the ice rarely afford safe paths, the student will, with a few hundred feet of climbing, find himself on some shoulder of rock which will give a view over the middle regions of the glacier. Now for the first time he may hope to perceive in its full glory the awful beauty of these great rivers of ice. From the wasted terminus he has just left, his eye may follow the long stream up its miles of steep ascent to the vast fields of snow where it has its beginning. The likeness to the streams of molten water is complete. On either side are the boundary walls of the mountains; through their curved ways we see the glacier widening when they go apart and contracting when they are brought near together, and from the side valleys come lesser streams of ice to mingle their tides with the main glacier. On the surface of the stream we perceive a vast quantity of stony waste gathered from the rocky walls of the mountains through which the glacier has passed on its road from the upper snows towards the terminal moraine. This waste is in a general way regularly distributed in a singular order. Near the sides of the stream there is a huddle of fragments which have fallen from the slopes of the bounding mountains. This is gathered here by the avalanches of ice and snow that in the spring and early summer rush from the steep uplands of the mountains with such force that they bear before them vast masses of rocks that may have been loosened by the winter frost or the summer lightnings. The ice and snow melt away, but the stones they brought with them are left to attest their work. If the observer can wait through one of these spring-time days, when the sun begins to deal with the heavy snows that have recently fallen on the mountains above, he may

see how the work is done. In the midst of the enduring silence that wraps these regions above the hum of life wherever the mountain streams flow unheard beneath their deep ice roofs, he will hear for miles away the sounds that mark the coming avalanche. At first the air seems to tremble without distinctly audible sound, then the mountains seem to be pulsating with a low thunder that rises as it nears to a roar like that made by an enraged sea upon its shore. Still the sound seems to be everywhere; we do not know where to look for its place. Finally, up among the peaks we see a rush of great stones that outrun the main tide of ice; behind these comes something like a moving wall of ice and stones and mud, all commingled together in a blackened mass that rushes like a waterfall down the steep. The great stones outrun the less heavy ice; at each leap they clear hundreds of feet; they seem possessed with a bird-like freedom in the air, and when they strike the ice they raise a cloud of splinters and bound far out into its field. Behind them comes the great burden of the avalanche, that pours on for it may be fifteen minutes, until it has brought to the ice a contribution of many thousands of tons, a considerable part of which consists of stones, sand, and mud it has swept away in its course. Such an accumulation is shown on the left side of Fig. 3. In this way, owing to the violence of the fall and their many rebounds, the stones are driven well out from the border into the field of the glacier. If the glacier be of considerable size and receive several tributaries, it will show in the middle part of its stream several lines of boulders like those which are formed in the manner just described. At first sight these central moraines are puzzling, but in a moment they are seen to be the lateral moraines of the tributary glaciers, which are necessarily thrown into the middle of the stream produced by their union. This will be more readily understood by the inspection of the accompanying diagram; by taking the number of these central moraines plus one, we can determine how many affluents go to make up the glacier. If there are three medial moraines, there will be four tributaries; if four moraines, there will be three branches; etc. If the point of view be not too remote from the ice stream, there are many other details connected with its

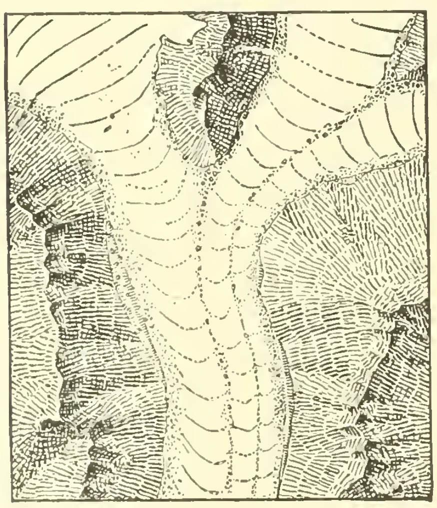


FIG. 2.
LATERAL AND MEDIAL MORAINES.

general structure that will be apparent to the eye. We see that the stream is not smooth as a river, but in places extremely irregular in its surface. On either side we see that the stream does not meet its banks as a river does, but there is a depression between the glacier and its boundary walls, as on the right in Fig. 3. Then across the glacier in an irregular way, but generally curving upward, there are very frequent fissures, some of which seem to cut the glacier almost in twain. When the slope is slight, the ice is for great distances compact and unfissured; when the stream passes over a slight convexity in its bed, it is wildly torn by these crevasses. Especially is this the case when the glacier pours down from the snow fields over the steep slopes that close the bends of the valleys. Even from a distance, if the point of view be high enough, we see that in place of united ice we have there a huddle of vast fragments, — prisms, obelisks, and pyramids of ice known as séracs, that are riven from the mass by the tension produced by the irregularities of the bottom over which it moves, and by the faster motion down the rapid incline. As these detached masses find their way slowly to the more even ground below, they close up the interspaces, solder their faces together, and move on as one mass.

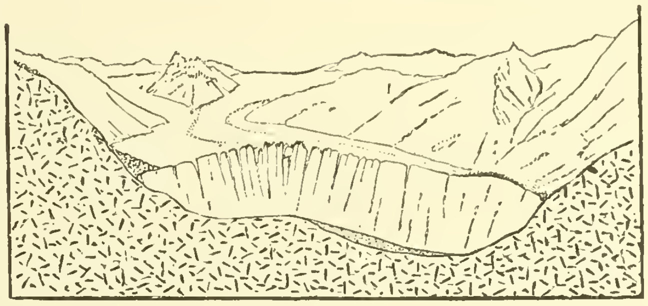


Fig. 3.

Cross-Section of a Glacier, showing its Longitudinal Crevasses.

After this general survey of the glacier from above we may pass to the nearer views that a walk over its surface will give. Clambering down the little valley that separates the ice from its bounding walls, we must scramble up over the lateral moraine on to the field of ice; mounting this slope, we find ourselves upon the surface of the glacier. The reader who has pictured to himself the ice of a glacier as having something of the blueness and purity we commonly associate with that substance will be disappointed. Beneath his feet is a dirty white floor, stained all over with the mud and sand that the streams that wander over its surface work out of the moraines. If we set foot upon the ice in early morning, we shall find our way nearly or quite dry. Here and there are thin sheets of new-made ice covering pools that froze when last evening's sun left the cold air to do its work, but the water has mostly drained away from them, and the thin ice has fallen into the cavity, except around the edges, where a shelf shows the depth to which

yesterday's melting filled them. As soon as the sun begins to do its work a sound of running water and falling stones slipping on the moraines awakes all over the ice, and by noonday the whole of its more level surface is covered by lakelets and rivulets that connect one with another; every now and then we come across a rushing brook that has carved itself a deep channel, a trough that is in every feature like those of the streams that course over the land. In them a bit of harder ice makes a rapid; a fissure turns its course, as a crevice in the rock might do. Even little terraces mark the successive stages of the downward cutting of its bed. If we follow the stream a little way, we find it joined by others, and the rivulet swollen sometimes to a considerable brook, that sweeps along the pebbles that come within its grasp, and finally sinks through the ice into a deep well-like opening that leads down to the roots of the glacier. Here for the first time we get an idea of the profound depths of the glacial mass. The stream tumbles down its moulin, as the well-like opening is called, with a roar that tells of vast depths and chambers below. Here and there we may find these moulins which have been deserted by the streams that carved them. By means of a stout rope and with a stout heart to help, we may gain the edge of the cup-like slope that surrounds the vertical well. The view well repays the risk, for the eye ranges down the crystal shaft through a light of wonderful blue, until it is limited by the darkness of the depths alone. In many cases these wells doubtless cut clear through to the base of the glacier, which may be even a thousand feet from the surface; but generally they seem to branch off into lateral galleries, and so find their devious way to the arches in which flow the sub-glacial streams. A little observation will show us how these moulins originate. They always begin in the narrow fissures in which the crevasses have their birth. The strains brought about by the slow movement of the glacier constantly expose its mass to the formation of breaks, which may heal by being pressed together immediately after their formation, or may be widened into the vast sundering fissures, to which we shall next attend. Although the whole mass of the ice is riven by these cracks, the observer will have perhaps to haunt it for weeks before he has a chance to see and hear them form. Some midsummer's day he will hear a cracking sound beneath his feet that seems to come from every part of the glacier; after this has continued for some time, he may see bubbles rising from the pools near him, and as they are on something like a right line he may determine the trend of the crevice, which is yet too narrow for the eye to perceive; searching closely on the side of

the pool, he will find its line, and the opening, which is often not more than perceptible on the closest scrutiny, can be found by noticing that there is a rush of air out of it. Whenever the glacier is newly riven this uprush of air occurs; this is worthy of note, for it shows that the ice is full of cavities containing air in a certain state of compression. This, as we shall see hereafter, is due to many causes: the constant closing together of the crevasses tends to imprison air in the ice; the chambers excavated by running water at times become compressed, without any outlet remaining for the escape of the imprisoned air; the falling of water through the crevices of the ice also serves to cause a certain amount of compression of air in the deeper cavities of the ice; moreover, there is no doubt that the snow, which we are to study in the upper fields whence the glaciers derive their supply, imprisons air as it falls, which does not altogether escape, when by time and pressure it is converted into ice. By some or all these means the air is provided that by its escape shows us the birthplace of a crevasse.

To come back to the rent that has just been formed, at first it is not perceptible save by the outrush of imprisoned air; but if we watch it even a few hours, we see that the difference in motion between the ice above and below its line has been enough to cause it to gape a small fraction of an inch, and in a few days it may become several inches in width. The first effect of the rent is that the streams that traversed its course find their way down through this fissure in the ice, and carve out the moulins we have seen. If the fissure widens rapidly, no moulin is formed, but the water precipitates itself down the sides of an extensive rent. If, as is more probable on the level regions of the ice where water gathers in streams, the fissure soon closes together again, all trace of a rent will disappear, and we shall only have the moulins to tell that there had ever been one there.

As we ascend along the glacier we are pretty certain to come to extensive parts of its surface where there are more distinct evidences of fissures than are furnished by the shafts of the moulins. We find places where the surface of the ice is sundered by profound crevasses. None of them run quite across the glacier, but their lines are so interlaced that we have to travel in most circuitous ways to gain our upward course; often the only path is along the narrow "horse-backs" that separate two deep chasms, into which the eye looks as far as the blue twilight will allow without reaching to the bottom. The chips from the guide's ice axe, as he cuts the steps of the dangerous way, fall from point to point down these fissures until the sound dies away in the depths.

These crevasses occur wherever the ice stream passes over some convexity in its bed. Even very slight projections will cause rents of this fashion. As soon as the moving ice has passed beyond them, its sundered fragments are again conjoined into a solid mass, such as we walked over when we first came upon its surface. In general, we may say that wherever the floor over which the ice moves is level or concave in the direction of the movement, the ice remains essentially unruptured in the central part of the stream; wherever it is convex, the ice, unable to stretch, — though, as we shall see, it may be squeezed, — breaks apart, as its quality of eminent brittleness compels it to do.

The passage of the ice down the high walls that bound the heads of these valleys (see diagram) gives it the most favorable conditions for rupture, for there the convexity of its bed is apt to be the greatest, and there we have always the wildest rending of the ice that can be found. Often this riving is so complete that the ice, which was a broad, unbroken sheet before, is now broken into a maze of separate masses, which march slowly down the steep, or plunge in headlong ruin down towards the region where they are to be again gathered into the solid mass of the glacier. We have already compared the glacier to a river; indeed, it is an analogy which forced itself upon the minds of the very earliest contemplators of these wonderful structures. The analogy extends to very many details of its structure. The moraines are like trains of driftwood, borne along by rivers near their banks; at a junction of streams, two trains come together and float on in a single line for a considerable distance below their union. The crevasses may be compared to the ripples that sweep over the surface when the current passes over an obstacle. The tumultuous dislocation at the heads of the valleys, in such a scheme of analogies, may be likened to the waterfalls so commonly seen in rivers when we pass from their broad valleys to the more rugged regions of the mountains where they rise.

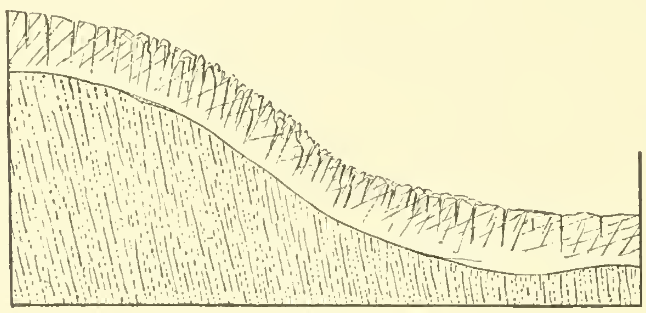


Fig. 4.

Longitudinal Section down an Ice-fall, showing the Séracs.

Before passing from the glacier proper to the regions of névé, or granular snow, whence they derive their support, there are some other details of their

structure that demand attention on account of the light they throw upon glacial forces, though they may not be of sufficient prominence to catch the eye.

Looking closely at the ice where it is exposed in the sides of the crevasses, we perceive that it is not of perfectly even texture; on the contrary, it is almost always laminated, or divided into thin layers that stand at a high angle to the surface of the ice. This structure is sometimes like the bands of a mass of agate in its beauty and distinctness, but more generally it is not so manifest as to command the attention of even an acute observer; indeed, it was not for many years after the study of glaciers was begun that it was perceived by the keen eye of a physicist, the most acute of all the observers that have ever worked on the problems of glacial structure. This structure is an enigma of which we have perhaps not found a solution, but, as far as we can observe the facts, it has certain curious and definite limitations. In the first place, we cannot find it above the limit of the upper region of the séracs. Then we see that it is remade in the ice after it has been previously obliterated by passing an icefall; still further that it always forms with its planes of the cleavage at right angles to the pressure that is at the time exerted on the ice. When we come to consider in an analytical way the origin of the phenomena of glaciers, we shall see that this structure is the effect of pressure, as the crevasses are the effect of the forces that tend to pull apart the ice. So these two phenomena are the indices of the two classes of strains that are at work in a glacier, — those that tend to push its parts more closely together, and those that tend to pull its parts asunder.

The surface of a glacier also shows some even less conspicuous peculiarities of contour, that, despite their inconspicuousness, deserve attention. Viewed from a height on the sides of its valley, an attentive eye, aided by favorable conditions of illumination, will perceive certain broad bands of light and shade traversing the glacier in the fashion indicated in the diagram; these bands follow the same general trend all through their course, but the eccentricity of their semi-ellipses increases as we descend the valley, until they fade out on the lower parts of the glacier. Although the existence of these bands is only discoverable by the general view that is to be obtained at a distance, their nature may be perceived when we come back to the ice surface. We then find them to be bands of dirty ice some scores of feet in width, separated by interspaces of ice that is of a clearer nature which appear white by contrast. Inspection shows us that this ice is only superficially discolored, and there can be no doubt that the cause of the discoloration

arises from the fact that these dirt bands occupy broad shallow depressions in the ice into which the water has washed the mud and sand from the rest of the surface.

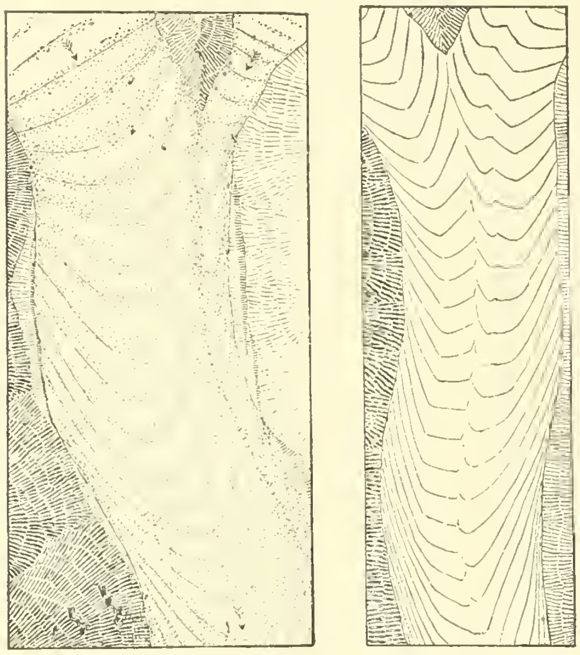


Fig. 5, *a* and *b*.

Dirt Bands on the Surface of a Glacier.

In the second cut the complex bands formed where two glaciers unite are outlined.

Sometimes these depressions, having caught the snow blown along the surface, or retained it longer under the heat of the sun on account of its greater depth there, may appear whiter than the surrounding ice. But the essence of their structure is that they are broad shallow depressions, which, when they first appear, extend across the glacier, curving slightly downwards towards its end. As they advance, the central part, on account of the more rapid movement of the middle of the ice stream, curves more and more downwards until the discolored bands form very extended figures, as is shown in Fig. 5. A close examination of Plate III. will show the same structure. The cause of these singular wrinkles will best be discussed when we come to a deliberate inquiry into the physics of glaciers.

There remain certain portions of the glacial surface which we will only glance at here, for they will have to be discussed more fully hereafter. Indeed, these strange fields abound in problems of intense interest, which we can hardly note at all in the first view of their surface. If the observer will so arrange his studies of glaciers that he may visit the same stream at different seasons of the year, he will be astonished to see the wide difference between the conditions of the ice in the summer and winter

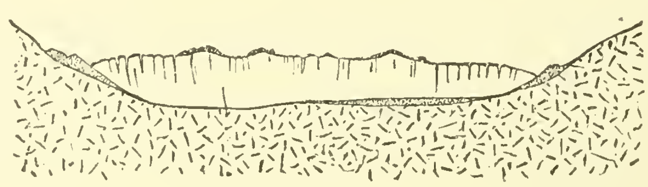


Fig. 6.

Cross-Section of a Glacier, showing Longitudinal Crevasses, and Medial, Lateral, and Ground Moraines.

periods. In the winter he will find these rent and worn fields in themselves a very type of ruin, all healed with snow; the glacier not worn and shrunken within the lateral moraines, as it is now (see Fig. 6), looking like a river in the time of drought, but flush to its banks of boulders and high arched with its abundant flood of ice. When months of spring and summer sun have done their work, the subsidence of the ice in the lower parts of the glacier is often from twenty to forty feet. We see evidence of this power of the sun and rain on every side of us. If the glaciers run nearly north and south, which happens to be the case with a great part of the Switzerland ice streams, the crevasses will have their trend in an east and west direction; there will therefore be one side of the crevasse that is particularly exposed to the action of the sun, and one that is sheltered from its influence. The result is to make a section across the crevasses have the outline given in Fig. 7. Then again the moraines are evidences of the superficial melting; they protect the surface beneath them by the non-conducting power of the rock that constitutes their long trains, and so they come to stand up on long ridges of ice,— an arrangement that tends to make us greatly overestimate the actual mass of their waste, for the eye mistakenly includes in it all their projection above the general level of the ice, while the débris is generally only a thin covering upon the surface of the glacier. This is made more apparent by the occasional table-rocks that stand here and there, lifted upon pedestals of ice that are always much narrower than the protecting cap. Wherever a stone lies a little remote from its neighbors, we have this sort of evidence of the wear of the ice. As the column becomes higher, the pedestal is more exposed to the

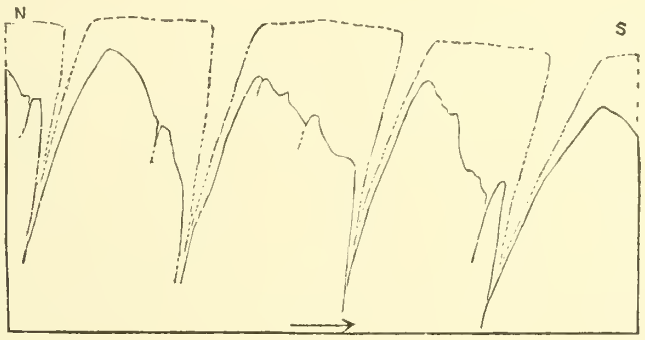


Fig. 7.

Old Séracs melted away on the Sunny Side.

Fig. 8.

Part of a Medial Moraine, with a Rock Table and Pebble Wells.

sun, and it finally becomes too weak for its burden, and allows it to fall again upon the surface of the glacier. The effect of small pebbles is just the opposite of that of large rocks. All the stones absorb more heat than the ice does, and so become comparatively warm in the daytime; but while the large blocks are too thick for this heat to penetrate them, the little pebbles allow the warmth to pass through to the ice beneath. In this way slender wells are formed, each with its pebble at the bottom, as much as a foot or more below the general surface. A group of such pools is shown on the right in Fig. 8. As these processes may be repeated several times during the score or two of years in which the ice is upon its journey from the sèracs to the terminal moraine, it is clear that there is no small downward wearing of the glacier in its slow onward course, and that its terminus is fixed more by the melting of its surface than any particular wasting of the very end itself.

We have now seen the more evident features of the surface of the glacier, those features that will be apparent on simple inspection, such as a tourist may make without the use of a great deal of time or instruments of precision. It would be possible to spend many weeks on this surface without exhausting the numerous minor details of structure which it would exhibit to the close inquirer; but, leaving for the present this strange world of the lower ice, we may pass on into the higher lands of the Alps, where are gathered the supplies of frozen matter that are sent down as glaciers to the lower levels.

The whole of the glacier proper lies below the level of permanent snows. In the winter it receives a great amount of snow from the usual storms, and a yet larger share from the drifting into its valley of the snow from the steep faces of the bordering mountains; but this snow makes no permanent addition to the mass of the glacier. Except when it drifts into crevasses or the deep valleys of the streams that fret the surface of the ice, where the movements of the glacier may compress it sufficiently, it does not become converted into ice, and disappears in the early days of summer, merely helping for a brief time to protect the glacier proper from the heat of the sun. It is not until we get above the line where the sun's rays have power enough to take away the snow during the summer, that we come to the region where the glaciers find the supply of ice that renews their wasting masses.

This snow line, though often represented as a geographically distinct line, has no such exact definition. It is at one point on steep slopes, whence the snow descends in avalanches; at another on the benches where the snow lies unshaken,

and where it is often fed by falls from above. Yet, as we climb up the sides of the mountain, we pass, within the limits of a few hundred feet, from the zone where summer does its work, though in a sorry fashion, to the region where winter holds unbroken sway. We pass the last stunted flowers, hastening to finish their task of blooming and seeding in the few days of their summer, and step upon the eternal snow, — eternal even in more than the common sense of the word, for it has endured while many a bold mountain-peak has withered in the long combat with frost and lightning.

At the first touch of the foot we perceive a difference between this surface of the upper snow, or névé, and the glacier to which we have become accustomed. The névé has the same color as the glacier; it too in midsummer is somewhat stained by the dust blown from the dry faces of the steeper slopes where the snow does not lie, but it is much smoother than the glacier. When it is not glazed by recent frost, the foot sinks into its surface; there are few or no fissures, and when a chance rent shows us its depths, it is only at some distance from the surface that they begin to take on the deep blue of the true glacial ice. Along the long vistas of the Alpine highlands, those great sloping fields that the mountains uphold on their strong shoulders, these snow areas stretch away upwards until only the hardier peaks escape above their billowy folds. While the glacier below has all the majesty that power can give, it has still something of the every-day active world about it. It lies near fields and habitations, flowers grow on its sides, insects abound on its surface, and now and then birds visit it; even its physical life gives familiar activities. It is pervaded by running waters, and their sound, with that of the constant fall of the stones of the crumbling moraines, relieves the weird aspect that its form alone might give. But to this upper world none of these elements of accustomed life belong. It is as soundless as a cavern, and the eye and ear find nothing of the usual world below. The work of the sun is powerless to animate either physical or organic life. We have escaped from its dominion into the province of that eternal cold that wraps the world about.

Coming to a closer study of the névé, we find much to invite our attention, much to aid our understanding of the processes whereby snow is converted into glacial ice. It requires but a moment to see the difference between this snow and that with which a winter's experience makes us familiar. As it falls, snow is generally at such altitudes composed of crystals of water of the beautiful forms with which our snows in midwinter make us acquainted. These crystals, when com-

pacted, are changed to a rather homogeneous mass, the separate crystals being matted together, holding a large amount of air in their interspaces. The greater part of the mass is finely divided air, which causes its white color. But here the névé is made up of granular bits, which, when closely examined, are seen to be not in the least like crystals, but are rather more like hail-stones, packed closely together. As we dig down a few inches from the surface, we find these ice spheres to be compacted more closely together, and if we penetrate two feet or so beneath the surface, we have a gradual passage to a solid mass, which is still whitish from the abundance of air it contains, but is essentially ice.

Something of the same sort may be seen when, after a long winter, snow lies upon the open fields of our New England hills. There, too, the snow becomes granular, and though it does not take on the distinct form of ice, we can complete the change by condensing it in a press until the exact condition of the deeper part of the névé may be reproduced. There can be no doubt that the passage from the falling snow crystals to the ice that joins the glacier proper over the ice-fall of the sérac is accomplished by the gradually increasing pressure of the sucessive snow-falls that continue, winter and summer, from age to age. To this we may add the pressure of ice that comes from the constant sliding downwards of this névé; for though it is not classed as a glacier, it has, with the developed ice stream below, this property of slowly and constantly creeping down its slopes. Although it is not often that we can get access to the depths of the névé, the undulation of its surface and the occasional fissures that we find on its edges make it plain that it has nothing like the depth of the Swiss glacier proper. While in the glacier we doubtless have depths of several hundred feet, probably in a few places exceeding a thousand feet, in the névé it is doubtful if the depth often exceeds a fifth or a sixth of that measure. Moreover, its movements are certainly on the average slower than those of the glacier, so it is possible to compress the snow supply of fields that occupy many times the surface of a glacier proper into the relatively small space of the ice stream. Something also is to be attributed to the expulsion of the air during the compression of the névé in passing from the stage of incoherent though somewhat compacted snow to true glacial ice. The mass must lose a large part of its bulk; just how much the imperfect study of the physics of this part of the glaçial system has not yet told us.

As the névé goes onwards towards the line of the séracs, or ice-falls at the head of the glacier, where it enters the mill that is to work it into the form of

glacial ice, it almost always finds itself compressed and deepened by the narrowing of its paths. It is a law of these mountain-top valleys that they narrow downwards, so that a part of the work of squeezing and compacting the névé is done before the sérac is attained.

We have spoken of this névé as fed by snow; in its lower part it doubtless receives some water in the shape of rain, but this essential absence of liquid water penetrating the ice of the deeper névé is in part the cause of some of its peculiarities.

It has been suggested that these regions of perpetual snow owe a good deal of their supply to the condensation of vapors which they effect from the winds that sweep up from below. We are all familiar with the simple experiment of condensation that takes place on the outside of a pitcher containing ice-water: it will sometimes happen that this water taken from the air will, in the course of a day, amount to nearly as much as the vessel contains. Something of the same kind has been supposed to take place on the ice of the névé. During the day the winds that stream up from below convey a considerable load of moisture, which they carry by virtue of their heat; striking this region of cold, and being chilled, they are compelled to lay it down. Especially does this deposit take place during the night-time, when through the rare air the temperature quickly falls far below the freezing-point, and the air which has risen from below is suddenly squeezed by the cold, as the hand would squeeze a sponge, and its moisture dropped as frozen dew on the snow. Every passing cloud, even if it drops neither rain nor snow upon the névé, yields it some moisture. There is no doubt that we have in this action a real cause of growth in the névé, but it may well be doubted whether the gain through this cause much exceeds the loss which takes place through the insensible evaporation that occurs during the times of sunshine. It is a well-known fact that ice and snow can waste by evaporation without perceptible melting; even on the coldest winter day, when the sun does not appear to touch the snow and ice, they pass into the dry atmosphere with considerable rapidity. It is probable that some slight gain in the volume of the névé takes place from this process of condensation, but it probably bears a rather small proportion to the mass of ice formed from the snow-fall. The average depth of ice that would be formed in the névé regions of Switzerland from the snow-fall that occurs there probably exceeds eight feet per annum. The rain-fall of the mountain districts averages nearly ninety inches, and, the névé districts being the recipients of a good deal of snow blown

from the more exposed and precipitous peaks, it probably exceeds this amount. If there be even as much as five feet of névé ice accumulated each year on these feeding-grounds of the glaciers, all the necessary supply would be obtained. At the known rates of motion of the névé it must be in most instances scores of years before the matter that falls on its upper edges finds its way to the glacier, so that the greatest depth we are called on to allow to the snow fields would be provided for.

Unlike the glacier, the névé is not exposed to any wasting; it is the seat of those actions alone that go to increase its mass. There is no considerable surface melting; hence the stones that may chance to fall upon its surface remain covered by the successive accumulations of snow, and do not appear in the shape of moraines. Nor does there seem to be any underrunning water in this region; some there may be arising from the internal heat of the earth and the friction of the ice on its bed, but this is unlikely. Being above the snow line, the ice of the névé is somewhat below the freezing-point, so the heat from these sources is probably all used in giving a slight elevation to the temperature of the névé without having any effect in producing melting. Indeed, we may divide a glacial area into two distinct regions on the basis of this melting alone, — the névé, or the seat of no melting but of constant increase; and the glacier proper, the seat of constant wasting, which is much increased in summer, but takes place, as we see by the constant outflow of sub-glacial streams, all the year round. The essential differences between the physical characters of the two regions are closely connected with these peculiarities.

Our preliminary glance at what may be called a typical glacier of the kind that abound in Switzerland has brought before the reader the most important of their external features. To complete the impression of the characters of existing glaciers, we must ask him to conceive a very different class of ice work; that which goes on upon the lands near either pole. All the glaciers of what we may call the Swiss type are, in fact, tongues of ice protruded from the region of eternal snow into the region where the sunshine gains upon the times of cold. As we go towards the north the descending snow line brings the glaciers nearer and nearer the sea level. In Europe they do not at any point gain the sea, except in Northern Norway at about seventy degrees of latitude. At no point in any of the great continents, in fact, do we have the region of perpetual snow brought so low that the ice may protrude its capes into the deep; but in the archipelagoes about

either pole we have vast regions where this takes place. In the lower latitudes of these regions of eternal ice the glaciers still have the general character of those we have been considering; they are still divisible into névé and glaciers proper. Though the névé may come down very near to the sea line, it does not actually attain to it; but a little farther north, where no such divisions exist, the snow line is as low as the sea line, and the lower element of the glacial system ceases to exist. As yet we know little of the conditions of these circumpolar ice-sheets, so that the statements we have to make are of a rather general character. If the traveller passes to the north along the west shore of Greenland, he can see the transitions from the Swiss class of glaciers to that which is peculiar to the regions very near to either pole. In the southern part of Greenland the line of eternal snow is several hundred feet above the line of the sea, and though the ice streams generally debouch into the sea in the heads of the fiords that border this remarkable coast, and have all the typical characteristics of the Swiss glaciers, yet they differ from them in certain striking ways, as in the scarcity of surface moraines and the comparative infrequency of crevasses. As we get near the highest degree of latitude attained by man, we pass into the region where the snow line finds its level at the shore. In this region glaciers lose the division into glaciers proper and névé, and the great fields of continuous accretion come to the very shore. So, when voyagers speak of the Humboldt glacier having a sea front of fifty miles, we should not conceive such a stream as the Mer de Glace, battling its way through a warm region to the shore, but rather such a mass as lies about the sources of an ordinary glacial system falling over the shore without any waste from the summer that is not made good by the subsequent winter's snows. In such a mass we miss the most characteristic features of true glaciers. There are no moraines, for the ice sheet rises by a gradual slope from the cliffs of the shore to the farthest internal regions to which we can attain. There is no trace of cleavage structure, at least none has been noted in these ice fields, and their products, the icebergs of the Atlantic, do not show this singular result of pressure. All the eroded material that they bear from the interior is torn from their beds, and borne along, as is the waste that is carried by the névé, not as by glaciers in the lower part of the mass of ice. Although the superficial streams of the Greenland glaciers seem to be nearly wanting, or at least small in amount, we are surprised to find that the sub-glacial streams are very powerful, riverlike indeed in size.

The surface of these northern ice fields at a distance from the shore has been

seen but by few observers and by no special student of glacial problems. From the imperfect records that have come to us it seems clear that it is essentially like the névé fields of the Alps, with certain modifications dependent probably on the great thickness of the ice and its consequent greater disregard in its amount for the regularities of the surface over which it moves. The Greenland névé seems more riven by fissures than that of normal glaciers; indeed, these are so abundant that they have formed a serious obstacle to the efforts of explorers to penetrate into the icy wildernesses of the interior of this buried continent. There can be no reasonable doubt, however, that if we should succeed in penetrating this gloomy land we should find a gradual ascent from the shore to its central parts, the whole being buried beneath the vast depth of the ice, whose thickness probably reaches to hundreds of feet.

We have no data for determining the average rate of motion of Greenland glaciers of this type. It is, however, doubtless rather slow compared with the glaciers of the Swiss type; it probably follows more nearly the laws of motion of the névé districts of the Alps. Allowing it a motion of three hundred feet per annum, and computing that the Humboldt glacier drains a region that extends back for three hundred miles, it would be five thousand years before the ice would pass from the most remote point to the shore. Assuming that the rain-fall of Greenland is great enough to make one foot of ice each year, — it doubtless exceeds that, — the ice would have a chance to grow to a thickness of about one mile during its course towards the sea, unless it passes away by sub-glacial melting. We should on this basis have to allow a greater depth to the Greenland ice than would be admitted by glacialists generally. This is a question to which we shall have again to return.

In one most important way these Greenland and other circumpolar glaciers differ from those of lower latitudes, — they originate the icebergs that constitute so important a geological as well as picturesque element in our seas of high latitudes. These icebergs are formed wherever glaciers enter water of considerable depth. In many glacial lakes we find floating masses of ice, — the beautiful Märjelen See on the side of the Aletsch glacier (Plate XVI.) presents us with examples of such floating ice, that are like enough to bergs to merit the name, though they differ in their origin very essentially from the icebergs. The true iceberg is a portion of the front of a glacier that has been pushed into the sea until the buoyancy of the ice causes a mass to break away from its attachments, rise to the surface,

and float away. Before this separation can take place the ice has generally to advance into water to the depth of several hundred feet, and its adhesion to the glacier behind it will cause a considerable protrusion into the deep water beyond the point where the ice would naturally float when separated from the parent mass. Thus, when the berg is severed, it is quite free to begin its journey in an unimpeded fashion. As most coasts are swept by considerable currents, and as the deeper streams that sweep from the poles move towards the equator, a perfect mechanism is provided for launching and carrying these great fragments of the polar glaciers towards the more temperate regions.

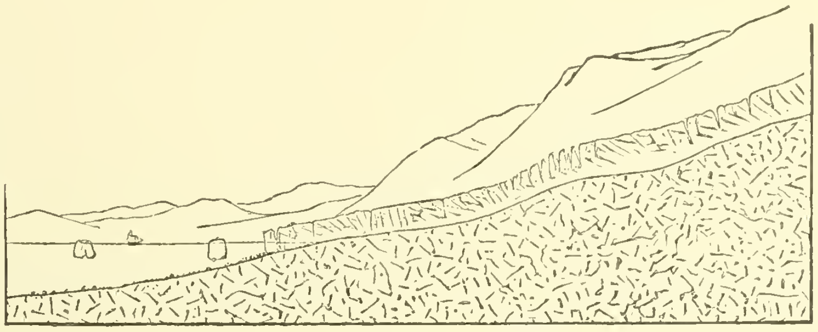


Fig. 9.

Formation of Icebergs, where a Glacier enters the Sea.

As the ice walls that supply such glaciers in our northern seas are several hundred miles in length, and as they have a seaward movement on the average of somewhere from one to three hundred feet per annum, the area of these bergs that are set free on their courses to the northern Atlantic is each year enormous; it not unlikely amounts to above one hundred square miles of bergs. This outflow of floating bergs is independent of the floe ice, or that which is formed on the surface of the water, which, from its great thickness, is often confounded with true glacial bergs. The berg ice immensely extends the work of the northern glaciers. In the first place, the escape of this vast mass of glacial matter into the more southern seas effects a great transferrence of temperature. There can be no doubt that the ice passing from the Arctic Circle to the regions south of it is competent to effect considerable lowering of temperature in the regions to which it moves, and in a certain way it lifts the temperature of the region it leaves; but the most important result in this direction is to remove the blockade of ice which would otherwise occur in the regions about the poles. But for this means of escape every avenue that traverses those archipelagoes would soon be closed, and the northern ice would extend itself southerly in such a fashion as to have a very serious effect on the climate of neighboring regions.

A considerable effect is, doubtless, also exercised by icebergs in carrying from

the lands over which they grind, large amounts of fragments that are dropped by the melting of the ice over the surface of the sea floors. The quantity of this débris is a matter of dispute. If we inspect ever so narrowly the bergs that float in the North Atlantic, we shall scarcely find any trace of stones upon their surface. This has been urged as an argument against the transporting power of icebergs, yet it should be considered that all the land waste of Arctic bergs must be frozen in the ice near their bottoms; for, as before stated, they usually have no moraine matter on their surfaces, and as they are not very likely to turn over until they have coursed considerable distances, the part of their mass that holds detrital materials would be very likely to melt away before the chance overturning of the berg exposed their under faces to view. The dredgings made in the track of the bergs that come from the vast glacial land of the Antarctic show that the bottom of the sea in that region is thickly strewn with waste that must have been derived from this source, and in the sea beds of other geological periods we occasionally find similar evidence of the transporting power of ice. Icebergs effect an important extension of the operation of glaciers, enabling these streams to exert powerful influence at a distance of a thousand miles from their natural termini.

While considering the action of ice in the northern seas it will be worth while to give a little attention to certain important varieties of its action which, though not strictly glacial, yet have close relations with that part of the work of ice to which we propose to limit ourselves.

When the snow line touches the sea level it is because the forces that take away the snow are no longer sufficiently active to overcome the annual accumulation. The existence of such an extremity of cold leads necessarily to the formation, on the surface of the land-locked seas of the circumpolar region, of very thick ice. This ice is composed of fresh water, and its formation tends to increase the salinity of the seas in this region. Sea water resists the action of frost, and will not freeze at the temperature of 30° Fahrenheit, and this temperature it maintains through a large part of the year. The result is that the floe ice, or that formed on the surface of the sea, does not melt in the summer as much as it freezes in the winter, and but for its drifting away to warmer regions would soon block all the fiords and straits of the Arctic archipelago. On the surface of this ice the snows of each winter accumulate and help to increase the thickness of the mass. The ice floes north of Baffin's Bay and the straits and inlets that enter

the Arctic Sea from the northward contain a great deal of this ice, that has a thickness of more than one hundred feet. In the sea into which, or rather on to which, the Nares expedition penetrated, the floe ice seems to be in a fashion impounded, so that it cannot escape freely to the southern regions. In its prison it appears to continue to drift and grow for ages, so that the name of Paleochrystic Sea, or sea of ancient ice, given it by the officers of the Nares expedition, is well deserved. This mass seems, in fact, to be essentially a floating névé, like that which covers Northern Greenland, in everything save the peculiarities that come from its formation on water. Its depth was not accurately determined, but its perfect continuity and vast extent, together with the great irregularities of its surface, make it likely that it exceeds anything in the shape of floe ice found in the regions known to polar explorers. It seems probable that the so-called Antarctic continent is nothing but an immense sheet of ice such as this Paleochrystic Sea would become if it were to increase in depth until it fastened on the bottom of the sea. Given a vast sheet of ice, wrapping the surface of a circumpolar sea, supposing it to grow from winter cold and snows more rapidly than the melting of the water could remove it, the result would be that the ice sheet would in time cleave to the bottom of the sea and become a true glacier, although any portion of its bed was below the level of the water. In view of the southward pointing of the southern continents, and the gradual falling out of land towards the south pole, this seems to me to be a more likely hypothesis than that which now finds expression in our geographies, where the presence of eternal ice is taken as evidence of a continental development of land in that region. So far, I believe, we have no sufficient evidence of the existence of any other surface than ice above the level of the water in that so-called Antarctic continent.

We may leave the subject of the appearance and structure of glaciers after this rapid sketch. A more complete account of their composition would lead us into details of a purely physical kind that are necessarily foreign to the plan of this work. Enough has been given to enable the reader to follow the discussion in the subsequent chapters, in which we shall try to show the natural basis upon which the development of glaciers rests, and their place in the economy of the earth.

CHAPTER III.

THE DISTRIBUTION OF EXISTING GLACIERS.

DISTRIBUTION ON THE SEVERAL CONTINENTS. — EXISTING GLACIERS OF EUROPE, SCANDINAVIA, ALPS, PYRENEES. — INDO-EUROPEAN CHAIN, — CAUCASUS, ASIA MINOR, HINDU KUSH, HIMALAYA, THIBET. — AFRICAN GLACIERS. — NEW ZEALAND GLACIERS. — SOUTH AMERICAN GLACIERS. — NORTH AMERICAN GLACIERS. — CIRCUMPOLAR GLACIERS. — SUMMARY OF THE FACTS CONCERNING GLACIATION. — COLD ALONE NOT SUFFICIENT TO CAUSE GLACIATION.

(See Map, Plate XXV.)

THE distribution of the glaciers now in existence on the earth's surface cannot be described in a complete way. We are still without information concerning the surface of some regions where glaciers must play a considerable part, but in general we may determine with tolerable accuracy the fields where these structures have any marked development.

In the first place, we may note the fact that glaciers certainly occur in considerable number upon all the continental masses except Africa and Australia, and in the former of those it is possible, though not probable, that there may exist regions of eternal snow, from which small glaciers may flow; and, secondly, of the great marine islands, — that is to say, islands remote from the continent, with water of a thousand fathoms between them and the main-land, — only New Zealand can be said to have glaciers.

Beginning with Europe, let us trace the glacial regions from the Atlantic shore eastward across Asia. On the northwest the outlying Scandinavian mountain system holds its largest field of snow and glaciers on the Jostedal highland; many scattered ice streams are found to the north and south, and among the latter are several glaciers on the line of now frequent pleasure-travel. Far north, in latitude 70°, a large snow-field sends an ice stream down to the sea level. On the other side of Russia the Ural Mountains are conspicuous for bearing no glaciers whatever.

On the Pyrenees the glaciers are now shrunk to small dimensions, and are generally limited to the moist northern slopes, as may be seen even on the higher summits of the range. In number they are reckoned at about one hundred, of which only one is described as of elongated river form.*

Eastward along the far-reaching Indo-European mountain chains, there is probably not a distance of four hundred miles where some trace of existing glaciers cannot be found. They are scantiest in regions of least rain-fall, as in Asia Minor and Persia, and most plentiful in those of large rain-fall, as in the Alps and the Himalaya. Looking at the Alps more in detail,* we find the number of glaciers set down at over a thousand, of which about one hundred are of river form, or of the so-called "first order" of De Saussure. Including the snow and névé areas with the ice, the total frozen surface equals 3,050 square kilometers (a little above a thousand square miles), or about one seventh of the mountainous Alpine region. In length, the Aletsch glacier, figured in Plates III. and IV., leads the list, measuring 21.3 kilometers from the névé to its foot. Twenty-four glaciers are over seven kilometers long, including six of more than twice this length. While the snow-line in the Alps varies from 2,500 to 2,900 meters in altitude, the larger glaciers descend to between 2,000 and 1,000 meters; but only one, that of Grindelwald, passes the lower limit, its foot being about 990 meters, well below the upper reach of cultivated fields and orchards. Interesting accounts of the features of the Swiss glaciers and of the incidents of excursions upon them may be found in the writings of Tyndall, Whymper, and others, and in the Journals of the several Alpine Clubs.

East from the Alps, the Caucasus first presents a snowy range of considerable length, bearing well-developed glaciers on both its slopes.

In Asia Minor the higher peaks hold some scattered glaciers, and in Persia a small glacier occurs on Demavend, the great volcano north of Teheran. Farther on, the Hindu Kush is known to bear many and long ice streams, but we find very little description of them. Coming to the Himalaya, the southernmost of the mighty plateau-bearing mountain systems of Asia, with the highest peaks of the world, there occur also the longest glaciers outside of the polar regions. In the Mustagh or Ice Mountains at the northwest end of the system, Godwin Austen describes† glaciers of immense length, some stretching between thirty and forty miles down

* E. Reclus, La Terre.

† Journal of the Royal Geographical Society. London, 1864. p. 19, with map.

their valleys: they resemble those of Switzerland, but all their features seem to be made after a much larger pattern. For the region east of Kashmir, Andrew Wilson * has given an interesting narrative of a long journey over high passes and extensive glaciers; he describes some of the glaciers so completely covered with earthy moraine at the foot that a scanty growth of grass may be found above the ice surface.

In Sir J. D. Hooker's "Himalayan Journals" (1855) will be found a general account of the high ranges about the longitude of Calcutta. Owing to the great snow-fall from the moist southerly winds, glaciers descend much lower on the southern than on the northern slope of these mountains.

The broad plateau of Thibet is abundantly high and cold enough to support glaciers in nearly all its parts, but its snow-fall is insufficient to supply them. The same may be said of nearly all the mountains to the north: the Kuen Lun, the Pamir Plateau, the Thian Shan, and the Altai systems are all much less glaciated, owing to the dryness of their climate, than ranges of equal height under more favorable conditions. Some of the higher peaks, however, catch enough snow to send ice streams down their valleys, but even the late explorations of this distant interior region by the Russians from the north and the English from the south give us insufficient particulars of their distribution.

In Africa the only mountains now known whose summits hold enough snow to make glaciers at all possible are on the eastern side of the continent. In Abyssinia, on the highest peak, the snow-line descends only a thousand feet, and no glaciers are found.† Just south of the equator, Kenia and Kilimanjaro are estimated at 20,000 feet, a height which is very likely exaggerated; the snow-line is placed nearly 4,000 feet lower, but no glaciers are noted. ‡ In South Africa the Drakenberg range exceeds, at its highest, 10,000 feet, and is described as "snowy"; but the occurrence of distinct glaciers is not recorded.

The mountains of Southern New Zealand, 13,000 feet at the highest, collect enough snow on their westward slopes to send down large glaciers to a low level, the lowest reaching 705 feet above the sea, § where the mean annual temperature ||

* The Abode of Snow. London, 1875.

† H. Berghaus in Behm's Geographisches Jahrbuch, 1866.

‡ Von der Decken, Journal of the Royal Geographical Society. London, 1864.

§ J. Haast, Geology of Canterbury, New Zealand, 1879; and Journal of the Royal Geographical Society, 1870, with map.

|| A. Wojeikof, Die Atmosphärische Circulation. Petermann's Geographische Mittheilungen, Ergänzungsheft 38, 1874.

is about the same as that of London, Philadelphia, or St. Louis. On the dryer eastern slope of the same range the lowest glacier recorded ends at 2,450 feet.

Coming to America, on the extreme south the fiords of the western coast receive blue glacier-ice into their deep waters, and float it away as icebergs. Going north, the very dry region of Upper Chili causes a shrinkage of the glaciers to the highest peaks, and they are absent altogether for long stretches; with increased altitude and rain-fall near the equator, several volcanic cones bear small glaciers.* From the equator northward, our northern boundary must be passed before glaciers become at all conspicuous. In Mexico, Orizaba and Ixtaccihuatl show small ice masses. In our own territory the most southern glaciers are those on Mount Shasta in Northern California, discovered by Mr. King in 1870,† the largest being four and a half miles in length, and the three small glaciers on the Wind River Range of the Rocky Mountains, discovered in 1878 by a party of the survey of the Territories under Dr. F. V. Hayden. Sliding snow or névé drifts in our Cordilleras have been sometimes described as true glaciers; it is probable, however, that no permanent masses of advancing ice exist south of the above mentioned. Farther north, the Cascade Range bears glaciers on Mount Hood in Oregon, and Mounts Rainier and Baker in Washington Territory. On Mount Rainier, Mr. Emmons‡ describes a glacier four or five miles wide and about ten miles long.

In British America,§ the Rocky Mountains bear only scattered glaciers in the higher valleys. Nearer the coast, and with greater snow-fall, they increase in number and size, until about Mount St. Elias ice reaches the sea-level. Beyond this the mountains lose so much in altitude as to make the glaciers unimportant.

Although the Swiss type of ice streams or mountain glaciers is principally developed in the great mountain chains of Europe and America, by far the most extensive and important existing glacial systems are those that lie in the seas and archipelagoes of the Arctic and Antarctic regions. These regions probably contain many times the volume of ice that exists in all the other glaciers of the

* H. Berghaus, Behm's Geographisches Jahrbuch, 1866. More definite information respecting these high peaks may be expected with the publication of Mr. Whymper's recent explorations.

† American Journal of Science, March, 1871. See, also, "Mountaineering in the Sierra Nevada," by Clarence King, 1872.

‡ American Geographical Society, March, 1877.

§ A full account of the present and past glaciation of all this region may be found in "The Climatic Changes of Later Geological Times," by J. D. Whitney. Memoirs of the Museum of Comparative Zoölogy at Harvard College, Vol. VII. No. 2.

world. As before remarked, their prominent characteristic is that they are not divided into distinct regions of névé and true glaciers, as in the streams that owe their existence to the elevation of a narrow mountain chain, but they are rather extensive and very deep névé regions, where the snow is converted into ice by the weight of the superimposed mass more than by the kneading action that takes place in a glacier of the ordinary type. Moreover, these névé glaciers of the polar regions differ in their work very widely from the stream glaciers of the Swiss type. They have no waste upon their surfaces in the shape of lateral and medial moraines, but do all their work of transporting detritus in the lower portions of their ice and in the streams of water that flow from the arches at their bottom. They also differ from the stream glaciers in the extent to which they give rise to icebergs, by means of which they extend their efforts to regions far beyond the limits of the polar circles.

Having thus followed the distribution of existing glaciers, let us consider next some of the geographical and climatic causes of their occurrence and absence. In preparation for this, it will be well to compare the map at the end of the volume with rain and temperature charts of the world as given in physical atlases. The regions where snow and ice accumulate may then be grouped as follows: —

First, the polar regions, of great cold and considerable precipitation: Greenland and the neighboring islands, and the so-called Antarctic Continent.

Second, mountain ranges along western coasts, outside of the trade-wind zones, in regions of heavy and frequent precipitation: Norway, New Zealand, Patagonia, and British Columbia.

Third, interior ranges of great height and considerable snow-fall: the Alps, Caucasus, Himalaya, etc.

Such glaciers as do not belong under any of these groups are local, of small extension, and are occasioned by the excessive height of isolated peaks overcoming conditions unfavorable to ice accumulation.

Well contrasted with the above-named glacial regions are certain others that are peculiar in their freedom from permanent snow and ice. Prominent among these are Eastern British America and Northeastern Siberia. The latter is especially fitted by its temperature for the development of a glacial sheet of the Greenland type. Much of its surface is colder than the Swiss mountains, and this low temperature would place it above the line of eternal snow, as is proven by the fact that the ground is frozen to the depth of several hundred feet; only a thin surface

layer melts during the summer season, as a skim of ice melts at midday on the névé of a glacier. Much the same may be said of the vast region from the valley of the Mackenzie River to the northern shores of Hudson's Bay; its temperature is as low as that of Greenland, and yet there is a peculiar absence of glaciers over all this part of North America east of the Cordilleras.

Again, in the Ural Mountains of Western Siberia we have a chain under much the same conditions, as regards direction, latitude, and elevation, as obtain in Scandinavia, where fine glaciers abound; yet the Urals contain no trace of such structures: the wind that strikes them has lost most of its moisture before penetrating so far from the sea, and they are left comparatively dry.

We see, then, that although a certain degree of cold is clearly of absolute necessity, it is equally clear that cold alone will not create a glacial system. Glaciers are as much limited by snow-fall as they are by temperature; they cannot maintain themselves unless the amount of moisture condensed upon them is considerable, and the more equatorial their position, other things being equal, the more considerable the snow-fall must be.

A little further inquiry will, however, show us that the distribution of the snow-fall through the year is a matter of as much importance as the other conditions which we have enumerated. In the Sierra Nevada of California the snow-fall in winter much exceeds anything that comes in the Alps. It is not uncommon for twenty or thirty feet of snow to be accumulated during the winter in the valleys of this range. The total rain-fall is probably much in excess of that which is found in some parts of the Alps that support abundant glaciers, and the mean annual temperature is certainly low enough to admit of glaciation, yet all this snow goes away before the long unbroken summer sunshine. The first condition of glaciation, that some of the snow shall be carried from the summer to the next winter, is not satisfied. Similar cases could be cited from other regions, but this will be sufficient to show us some of the essential climatal limitations of glaciation. It is apparently necessary that the following conditions should occur: 1st, cold of considerable intensity; 2d, a considerable snow-fall; 3d, the absence of a very long drought period in the year; or, in other words, it is necessary that the snow of one winter should not disappear before the subsequent snow season. No matter how intense the cold or how ample the snow-fall, if the assemblage of climatal conditions does not favor the collection and preservation of the snow, glaciers will not exist. This may seem the statement of a self-evident proposition, but the fact has been so generally overlooked that it needs to be distinctly stated.

CHAPTER IV.

THE DISTRIBUTION OF ANCIENT GLACIERS.

Ancient Glaciers more Extensive than Modern. — Ephemeral Nature of Record. — Ancient Glaciers of Switzerland, Pyrenees, Corsica, Central France, Northern Europe, Great Britain, Asia, New Zealand, and North America. — Labors of Agassiz. — Southern Face of American Ice Sheet. — Rocky Mountains. — Continuous Nature of American Ice Sheet. — Ice Records in New England. — Depth of the Ice. — Ice in South America.

(See Map, Plate XXV.)

THE most remarkable fact that has been discovered by geologists during this century is, that at various times in the earth's history the glaciers, which now cover but a very small space on the earth's surface, certainly not over about one hundredth of its area of land, have been extended until they occupied a very large part of land and sea. The history of this important discovery we shall consider elsewhere, but in order that we may have before us the outline of what is known concerning glaciers, it will now be necessary to trace the former limits of the ice in its various periods of wide extension as far as our present knowledge will allow.

We now know that the earth is just escaping from one of its ice periods; that the last glacial time brought an ice mantle over the greater part of Northern Europe and over our continent down to the middle of its area, and that beyond the tropics, and perhaps in some cases within them, these ice sheets stretched out until they buried wide lands beneath their surfaces. The last glacial period is the only one of these ancient ice times that is or ever can be well known to us. As is easily seen, glacial action, of all forms of geological activity, is the most transient in its effect. Nature is like the fabled Sibyl, who from one visit to the other destroyed the most of the records in her keeping. This glacial record is the most ephemeral of all; at best, it lasts only until another visitation of ice comes to sweep it away.

Unfortunately for the purposes of our summary, the study of this record of the ice time which is just passing away is only now begun. It is hardly thirty years since geologists began to look at it with their eyes open, and although a certain amount of study had previously been given to these deposits, it was from an entirely mistaken point of view as to their origin and nature. As long as students endeavored to see in them evidences of a vast cataclysm involving a change in the earth's axis of rotation, or the product of icebergs wandering over a submerged land, it was impossible to make any real progress in their interpretation.

The most noteworthy fact connected with the distribution of the ancient glaciers — a fact that goes far to give us a clue to their true nature — is that they were most extensive in those regions where glaciation now exists, or where the conditions are very near to those which permit the formation of such ice sheets. Beginning with Switzerland, a classic ground for ancient as well as existing glaciers, we find that during the last ice time the ice was at least a hundred-fold as extensive as it now is there. The Alps proper, from the Tyrol to the valley of Switzerland, that great upland plain that separates the Alps from the Jura, were submerged beneath a very sea of ice. In the central region a few peaks and islands, such as the steep needles and fragments that baffle the feet of the chamois or his human imitator, the Alpine Club man, lifted their heads above this sea, but all the valleys of Switzerland were, during the deepest stages of the ice time, actually blotted out. Out of the Rhone, the Dranse, and the other streams that debouch here, those commingled ice rivers swept, filling the plain of Switzerland to the depth of over four thousand feet, and landing the waste, borne from the peaks a hundred miles away, on the eastern slopes of the Jura Mountains at a height of two thousand feet above the plain. On the south side of the Alps these streams, joined in one huge ice front, swept down upon the Lombardian plain near the line of the Po. On the north of the Alps the ice had a less extension, but it reached to the falls of the Rhine or beyond, and covered all the region to beyond the borders of Switzerland. Of the limits of this ice in the eastern Alps less is known, yet it is likely that the whole of the section of the Indo-European chain from the Jura to the Balkan was more or less deeply wrapped in this ice sheet. We do not accurately know the extreme depth of ice in Switzerland, but it must have been at least six thousand feet deep over what is now the Lake of Geneva; and in the gorges of its great valleys, as, for instance, between the Dent du Midi and the Dent de Morcles, it probably exceeded this depth. It

is clear that this majestic ice mass, while it surpassed the borders of the valleys beneath it, was at the same time guided in its movements by them, and did not neglect their boundaries, as it did in many other lands. The scratches that mark its course show that at its bottom, at least, it followed in its movements the course now pursued by the larger rivers of the country, and was, in fact, a number of separated streams coalescing on their upper boundaries in the vast névé that smothered the land.

The Pyrenees, which at present have only few and relatively inconsiderable glaciers, had, during the glacial period, a deep mantle of ice that extended to their bases. Corsica was at points glaciated; the Apennines, probably as far south as Rome, had some glaciers; in their higher valleys the volcanic mountains of Central France, especially those in the Cantal section, developed small ice streams. The Jura and the Vosges were, doubtless, the seats of ice action. But the whole of the region north of the Alps up to the northern part of Prussia affords us little evidence of glaciation, and we must pass beyond the continental part of Northern Europe before we find much that can be regarded as certain evidence of considerable glaciers. In the Scandinavian peninsula and Great Britain, which for our purpose are to be regarded as one region, we find the greatest evidence of glaciation that Europe affords. Stretching from Scandinavia across the North Sea, which it must have nearly closed, the North European glacier extended over Scotland, all the North of England, and probably all of Ireland. On the north its limits were perhaps the polar ice itself, and in the west the deeper waters of the Atlantic. The southern limit of this ice sheet was in the south-central part of England. It seems pretty certain that it did not extend beyond London, for no glacial matter of a distinctly unarranged form is found so far south. On the Continent there is no distinct evidence that any part of the region south of Denmark was covered by it. Considering that this sheet filled the northern part of the North Sea, it is not unreasonable to suppose, as we have above suggested, that it was the southern edge of the Polar ice tops rather than a local system of glacial sheets.

In Asia we have as yet very little information concerning the former extension of glaciers during the last or any previous ice age. We only know that the existing glaciers in Northern India have evidently shrunk, as those in, Switzerland have. In Africa we have reports of what seems to have been glacial action in the Atlas Mountains, and in the region about the Cape there are distinct evidences of the same work. In Australia the marks of glaciation, if such marks there be, are

extremely obscure. This is essentially the dry continent, and, as we shall see hereafter, it is in such a land that we should least expect the marks of glacial activity. In the neighboring island of New Zealand, where the glaciers of to-day push their tongues of ice down to within sight of the tree ferns and other sub-tropical vegetation, we have marks of a former extension of glaciers much beyond their present limits. It is, however, to the American continent that we must look for the most extensive development of the ice sheets of the last glacial periods. Especially in North America do we find the most admirable evidence of the magnitude and effectiveness of these ancient glaciers. On this continent the action of the old glaciers has been more carefully studied than in any other region of the same size. Agassiz, the real founder of glacial geology, brought here a very extensive experience in European fields. His enthusiasm for the subject, and his extensive influence with American students, have served to make this country the seat of very many inquiries in this class of questions. As we shall see hereafter, glacial phenomena in America differ pretty widely from those of Europe in many puzzling ways, so that it is necessary to become acquainted with both forms of ice action before we can construct any adequate conception of the conditions of the ice time.

Considering, for the present, the distribution of North American glaciers, we are struck with the fact that the ancient glaciers of America were more united and more massive than those of any other country. In Europe the glacial period brought no general ice envelope, covering the whole country, but gave rise to a set of separate glacial centres, from which the ice streamed only a little way on to the plains; it is only in its northernmost parts that anything like a continuous glacial sheet connected with the ice of the polar regions could have existed. In North America, however, we had quite other conditions; here the ice lay as a continuous mass, stretching down from the polar regions to the central parts of the continent, overlapping the shores for a great distance to the south along the Atlantic and Pacific coasts, and giving a continuous though irregular ice front across the land from sea to sea. Beginning with the existing circumpolar glaciers of the north, we may trace the ancient ice line down the Atlantic coast. From Greenland to the mouth of the Hudson the edge of this glacial mass, during the period of greatest ice action, lay some distance to the seaward of the shore; forming such an ice line as is now situated along the coasts of Greenland, where the Humboldt glacier stretches its crystal wall. It is not yet possible to trace this old ice front with accuracy, but it is pretty clear that it lay some distance to the seaward of all the present shore.

At some points we can trace, formed along this ice wall, the old moraines. The Banks of Newfoundland, George's Banks, and the other shoals of the Gulf of Maine, are a part of this old moraine. As we go south, this moraine lies nearer the shore and in shallower water, and therefore protrudes above its surface. In Cape Cod, Martha's Vineyard, Block and Long Islands, we have the southern part of its length in admirable continuity. From Long Island it passes to the land, the ice apparently not having occupied a position beyond the coast south of that point. The constant wearing of the sea, and especially the continuous breaking away of icebergs, kept the sea front of the ice within a rather limited range of place; but when we come to follow the old ice line over the land, we find that the variations of its position deprive the terminal or frontal moraine of its distinct character. In a general way, however, we can trace it through Central New Jersey, and south as far as Washington we are tolerably sure of its place; but south of that point the ice grew thinner and rose rapidly into the hills in Southern Virginia. Its shape was changed: it was no longer a continuous sheet, but was rather a set of small ice masses in the separate mountain ridges; and this character of thinness and weakness of effects continued to the southern outlines in the high mountains of North Carolina. Striking west through what is now West Virginia, we find again traces of the massive ice sheet which crossed the Ohio, somewhere near the mouth of the Kanawha River, and from that point to Cincinnati its line lay close to the north bank of the Ohio River. At no point did it cross the line of that stream, except perhaps for a brief time a little west of Cincinnati, where it may have overlapped the river and extended south of it for a distance of not more than ten or twelve miles.* West of Cincinnati the front of the ice sheet inclined rapidly to the northwest, and becomes hard to trace. It probably passed somewhat south of Chicago, through Iowa, and thence through Minnesota, following near the line of the Missouri to the Rocky Mountains. The Black Hills probably formed an outlier, having its proper glacial sheet. In the Cordilleras of North America the ice was lifted into high levels, and in accordance with the laws that affect the distribution of glaciers extended much farther to the south than it did on the plains. North of the limits of the United States we know little of its distribution; south of that line it covered a part of the mountain belt down to the limit of about seven thousand feet above the sea, as far as Southern

* These statements in good part rest upon unpublished individual observations on the southward extension of glaciation in this region. — N. S. S.

Colorado; farther on, its distribution is doubtful. For the belt of country along the Union and Central Pacific railroads, Mr. Clarence King gives, in Vol. I. of the "Fortieth Parallel Survey," a map showing the former extension of glaciers, from which their local character is at once seen. From the same authority we may quote (pp. 467–476) the following figures as establishing the points to which some of the old glaciers descended. On the east slope of the Front or Colorado Range they nearly reached the Plains, halting at 6,500 feet. From the Park Range, seventy miles farther west, their average ending was at 8,000 feet. On the Uinta Range, the largest continuous sheet occurred, measuring ninety miles east and west, and fifty miles between extreme limits north and south; on the northern slope, the glaciers descended to about 8,000 feet; on the southern, to 6,500. From the Wahsatch Range, falling steeply to the Great Basin, the ice pushed down to 5,000 feet. The Great Basin Ranges held only insignificant glaciers, of which the lowest came down to 6,500 feet. Extensive ice sheets did not exist beyond the Mexican line, yet there are good reasons for suspecting that on the higher points, especially where the rain-fall was large, there may have been local glaciers for a much greater distance to the south. The late Mr. Thomas Belt, a very good observer despite his speculative views on many geological questions, discovered some moraine-like heaps on the north shore of the Lake of Nicaragua in Central America, which he believed, and apparently with reason, were the work of ice. The recent discovery of glaciers at a greater elevation in the Cordilleras of Ecuador makes this appear less doubtful than it has hitherto seemed.

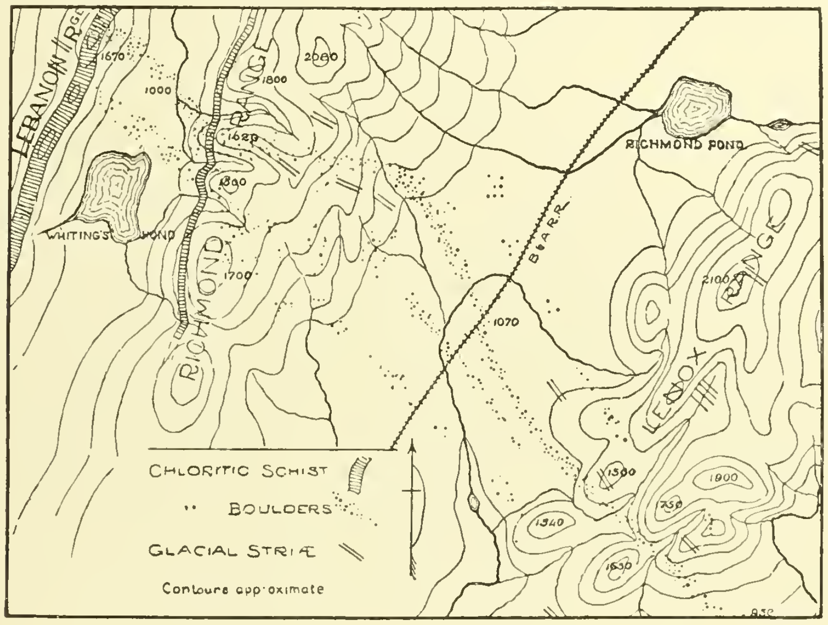
On the western face of the Cordilleras the last glacial period carried its glaciers down the west face of the Sierra Nevada as low as twenty-five hundred feet. The ice possibly came to the sea level near the line of Mount Shasta, and from that point northward probably overlapped the shore, as it did upon the eastern coast of North America. Of its moraines along the Pacific coast we as yet know nothing; but the fiord character of that coast, for reasons which will be given when we come to discuss the action of continental glaciers, is reasonable evidence that the ice overreached the present shore line in that region. Indeed, it would require but a relatively slight extension of the present glaciers of the Pacific coast north of Oregon to bring the ice streams beyond the shore line at many points. Thus, the American glacial system is seen in the east at least to partake of the massive and united character that belongs to all the aspects of its

structure. The region from the central part of the Mississippi Valley to the Arctic Sea is essentially united in its mass, and it is quite in the order of nature that this unity of structure should be marked in the climate that the glacial period brought to it.

There can be little doubt that the ice sheet was continuous from its southern face to the poles during the depths of the last ice time; although we know little of the detailed structure of this great area, its geography is sufficient evidence of the fact that glaciation has most effectively done its work over every part of its area. Throughout it is worn into the peculiarly uneven surface that glaciers alone can produce. Any good map will show a few of the myriad lakes that lie in the hollows of this uneven face, but a journey over its surface would show that not one in a hundred of the smaller basins has ever been put upon a map. The only agent competent to produce such a surface is ice; running water can never carve a lake basin in such rocks as occupy that region. This glaciated region of North America includes more than half the continent; in fact, over two thirds of its surface felt the weight of the ice during the last geological period, and marks its work in the existing geography.

When we come to consider the depth of the ice in this region we find less clear evidence than that which enables us to judge its horizontal extension; yet there are certain facts that go to show that its entire thickness was as surprising as the extent of the surface it covered. In New England the ice sheet has left for us a number of records that serve to show the minimum depth that we can assign to it. Wherever this ice sheet overrides the tops of mountains we may be sure that the ice much exceeded their summits. The existing glaciers show us unmistakably that the erosion effected by the ice will not be effectively accomplished unless the ice has a considerable depth above the given surface of rock. So when we have mountains standing somewhat isolated in the midst of great valleys, with the glacial scratches pursuing their usual course up their northern and down their southern flanks, we are perforce driven to believe that when the ice sheet lay over them the stream was so massive that the mountain was a relatively insignificant obstacle to its flow. If the mountain had only been buried for a slight depth below the ice, the glacier would have been deflected to either side. But in all the cases known to me, mountains buried beneath the glaciers of New England have glacial scratches driven up their northern faces, even though the general direction of the ice may have been somewhat affected by the obstacle. In the case of Mount

Washington, the highest American mountain of which we know the glacial history with anything like completeness, it is tolerably certain that the ice went over it, as a river goes over a pebble, only slightly deflected by the obstacle. It seems impossible to believe that the ice above the obstacle was not deep enough to force the stream to disregard it, or, in other words, to push and drag the ice over the barrier. Mount Washington is about sixty-three hundred feet above the sea, and may be estimated at five thousand feet above the neighboring table-lands on either



side. We are, therefore, driven to believe that the ice was more than a mile in depth, and it is difficult to imagine how the work could have been done as it has been done without much more than that depth. Nearer the Atlantic coast we find lesser elevations — such as Wachuset Mountain in Massachusetts, which is twenty-one hundred feet high — similarly overtopped by the ice. The Berkshire Hills, which rise on the east side of the Hudson Valley, lie oblique to the general run of the glacial movement. Their general course is north-northeast, while the run of the glacial scratches and boulder trains is about from N. 40° W. to S. 40° E.*

* This interesting region has been carefully described and mapped by Mr. E. R. Benton in the Bulletin of the Museum of Comparative Zoölogy, V. 17, from which the above sketch has been prepared.

If the ice had not been very much higher than these mountains, it would have been deflected by them; but it passed over their range, scarcely feeling their influence.

As we go farther west we have similar evidence of great depth. In the valley of the Ohio and the St. Lawrence we have evidence that the glaciers stretched from the Laurentian Hills to the Ohio River at Cincinnati. There is reason to believe that the Great Lakes existed before the last ice period; if this is the case, we must have had a continuous slope of the ice surface from the north across Lake Erie to the Ohio. This would require a great depth of ice in the region of the lakes, — a depth that we cannot well estimate, but must deem profound.

In the region of the Rocky Mountains we have little basis for asserting the depth of the ice. All the facts of the geology of the Colorado region point to the conclusion that the ice streams of that region were large examples of the Swiss type. Their remains show us streams of ice at some points scores of miles in length, with a depth of several thousand feet, but always limited to the great valleys where they originated, and not flowing out on the great lowland plains, nor overtopping the powerful mountains of the region. South Park seems to have been a reservoir of ice, out of which flowed the tributaries of such great glaciers as that of the Arkansas River, equal to the stream which, during the last ice time, flowed down the valley of the Rhine. All the evidence of an assured kind concerning the glaciers of the Cordilleras points to the conclusion that the ice was thinner there than in New England, that it was composed of distinct glaciers and not of a great connected sheet, and that it disappeared sooner in the decline of the ice time. The pebbles left by these glaciers are much more decayed and more cemented together than in the eastern districts of America.

Of the ice in the high northern districts of North America during the great glacial period we know nothing save by unsatisfactory evidence. It seems clear that its excavating power in that region was greater than in the more southern countries, where we have fuller knowledge. The depression of the land during the ice time, of which we shall have more to say in the next chapter, increases as we go northward; and as this depression seems to have been proportionate to the thickness of the ice, it affords a probability that the ice increased its thickness in that direction. We have another and stronger, though perhaps not a perfect, proof that this was the case in the fact that wherever glacial scratches have been observed, even in pretty high latitudes, they generally show that the

movement was out from the northern centre of the continent; it seems necessary to believe, therefore, that the ice grew thicker from the southern to the northern regions, else there could not have been a general movement from north to south. There is no slope down which the ice could have flowed, and in place of a slope the only thing that one can imagine to direct this motion would have been a greater thickness of ice in the region whence the stream came.

On the South American Continent we had a less extensive development of ice than the Northern Continent afforded. We as yet know little of the ice work in this hemisphere; we are not yet sure that it was done at the same time as that in the northern countries. Yet the evident likeness of the glacial remains in the two hemispheres seems to make it probable that they are of the same date. So far all the observations in South America are limited to the coast line. From imperfect studies, together with the character of the shore line, — in itself excellent proof, — it is fairly clear that ice action on the east coast did not extend north of the River Platte, nor on the west beyond the part of the Chili coast that is fringed with islands.* This would bring the ice over a much smaller part of South America than it occupied in North America.

There has been a good deal of discussion concerning the former existence of glaciers in the valley of the Amazon. Agassiz, to whom we owe the first suggestion of the value of glaciation as a great geological agent, at one time thought it likely that the valley of this great river had been the seat of a glacier that poured its ice from the Andes nearly down to the sea. This, which was hardly more than a suggestion put forth for the discussion of geological students, was, I believe, practically abandoned by this illustrious naturalist before his death,† and has been found to be an essentially mistaken view. The late Professor Hartt, geologist of Brazil, at one time thought some of the débris in the mountain districts near Rio Janeiro was of glacial origin, but this suggestion has never been submitted to discussion, and can have no weight against the other evidence of a negative kind that goes to show that glaciation, save in higher mountain countries, has never extended into the intertropical regions. Along the west shore

* The late Count Pourtalès made, during his journey with the Hassler Expedition, some very interesting observations upon the work of old glaciers on this coast. He promised me a statement concerning his studies on this point for this volume, but untimely death has deprived us of this important record. — N. S. S.

† In this assertion I have embodied the results of several remarks by my late master on this subject made during the last two years of his life. It is satisfactory to know that the only considerable mistake he made in the matter of glaciation was corrected by his own reflections on the subject. — N. S. S.

of South America there still exist, as the recent explorations of Mr. Whymper have shown, some small glaciers nearly under the equator. It is reasonable to suppose that these had a much greater extension during the last glacial period, yet we must wait for the investigations of geologists before we can know the facts.

An inspection of the map at the end of this volume (Plate XXV.) will show the reader that the most extensive development of existing glaciers is found upon the lands that surround the basin of the North Atlantic. From this map it is also clear that during the last ice period the only glaciers deserving the name of continental ice sheets were formed in the same region. Although the conditions that brought about glaciation were doubtless world-wide in their extension, it is clear that some cause or combination of causes brought about the formation of much wider ice fields in this part of the earth than in any other.

This brief résumé of the little that is known of the ice limits in the last glacial period makes it clear that during this time the earth was in a very peculiar condition of climate, and that geological work of a singular sort was under way over a large part of its surface. We will now proceed to consider the nature of the work done by glaciers, and the results of their action upon the land and sea.

CHAPTER V.

THE WORK OF THE GLACIAL TIME.

Action of Water in Rivers and Glaciers compared. — Effects of Weight in Glaciers. — Action of Subglacial Streams. — Excavation of Lake Basins. — Shock and Lea. — Boulder Trains. — Erosion in New England. — Frontal Moraines of Continental Glacier. — Retreat of Glacier. — Lenticular Hills. — Terrace Deposits. — Kames.

IN both its forms of fluid and solid, water acts upon the land as an eroding agent. In both these forms its principal work is done by virtue of the gravitative force it has when it falls from the air upon the surface of the earth. Yet in these two modes of action the results are very different. When water acts upon land in the usual fashion, the rain at its first impact gives a slight blow to the surface, that is generally rendered ineffective by the vegetable covering of the rocks. Then it passes into either the soil or the rocks below, where it acts as a solvent, taking away, in the state of solution, something of all the substances that the sea originally built into the land, in order that they may be returned to the deep to be used in building the lands yet to be. The ground water, as we may term the share of the rain that enters into the earth, penetrates to amazing depths, and exercises a variety of functions, in the erosion of caverns and the making of mineral veins, that it would require a volume to set forth. Finally, it emerges from the earth, finds its way again to the streams, and, combined with the water that has remained on the surface, does the peculiar work of erosion that is shown in the machinery of the rivers. Thus the work of molten water on the land is divided into two distinct rôles, that of the ground water and that of the surface water. Surface water has little dissolving power, such as is exercised by ground water: its principal effect is in wearing away the land by its mechanical power, that is, by the gravitative

force that bears it onward towards the sea; yet only a small part of this power is effectively applied upon the earth's surface; by far the greater part is used up in overcoming the frictions it encounters on its way. It is only when the water succeeds in rubbing one stone against another, or pushing the sand over the stones, that any effective work of destruction is done by it. The occasions when it can do this work are limited, so that the greater part of the gravitative force of water is spent in movements that are ineffective of any permanent results upon the land.

On the other hand, when the water falls as snow and makes its journey down to the sea in a glacier, a very much larger part of its gravitative force is applied to the land; practically all of it goes to the work of bruising and wearing the rock surface over which it moves. Then this wearing of ice is not in distinct lines, as in the work of fluid water, which wears mechanically only when gathered into streams, but is distributed over the whole surface of the land in a measure proportionate to the depth of the ice and the speed of its flow.

This extensive work of mechanical erosion effected by glaciers is accomplished at the sacrifice of the chemical work of water. As before remarked, rain-water charged with carbonic and other gases, penetrating the earth, exercises an almost infinite series of metamorphic effects. Glacial water, even when it exists as water, not passing through a coating of decaying vegetable matter, such as rain-water encounters in the soil, wants these gases, and is thus incapable of this metamorphic and dissolving power. Moreover, glaciers, though they doubtless have much water beneath their masses, have it gathered into streams heavily charged with mechanical sediment, and thereby incapable of doing the work that the rain-water, by its large capacity for taking up sediments, accomplishes. In brief, we may say that when a country is glaciated it entirely changes the rôle of water; chemical action nearly ceases, and in place of it we have a great addition to the mechanical action that goes on upon its surface.

This glance at the general differences between the conditions of operation of glaciers and rain-water will show us at once the importance of a more careful inquiry into the peculiar forces brought to bear upon the land by the sheets of ice that, during glacial periods, cover so much of its surface.

First, let us notice the enormous forces that are brought to bear through the weight of the ice, which often exceeded a mile in depth, and probably in some regions attained a thickness of more than twice this amount. This is equal to a pressure of from one hundred and fifty to two hundred tons to the square foot

on the rocks beneath the ice, in itself enough to crush rocks when they are not coherent and supported on every side. Now, if we consider that this mass was slowly dragged over the surface on which it rested, and that it was armed with the broken-up waste of the rocks which it had previously destroyed, the harder bits being selected as tools and firmly set in the matrix of ice, we get an idea of the enormous eroding power exercised by glaciers of the continental type. We see that from beneath an Alpine glacier, where the average depth of the ice does not perhaps exceed two or three hundred feet, there emerges a turbid stream, that hour by hour carries away a great mass of insoluble waste, the grist of the ice-mill from which it runs. The next valley of equal size, if it have no glacier, shows a stream that does not in a year carry as much sediment as the subglacial stream will run in a few days. Now, as the wearing of a glacier, other things being equal, depends on the depth of the ice, it is easy to see that such glaciers as once filled the valleys of Switzerland or the Hudson, or wrapped around Mount Washington, must have exercised many times the crushing force that we find in operation in our existing glaciers. As the ice stream creeps down from the highlands to the sea, or to the region where the melting arrests its farther progress, it applies slowly, but effectively, almost all the power that is given it by gravitation to this work of wearing away the land. If the streams that flow beneath it are incapable of carrying away the waste torn by the ice from the rocks, this mass of ruin is frozen into the ice, adding to its weight and grinding power.

It is important to notice the fact, already tolerably evident from the consideration of the effect of the weight of the glacier, that ice cuts with an energy pro-

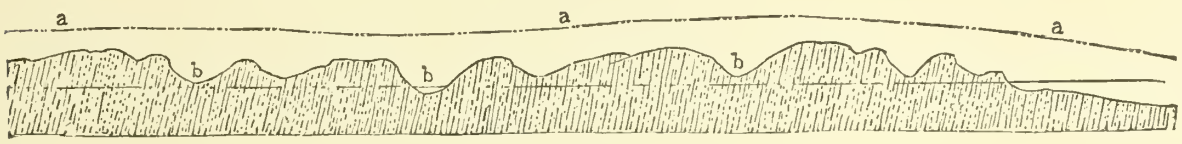


Fig. 11.

Cross-Section, showing the varying Depth of a Glacial Sheet.

a, a, a, surface of the ice.
b, b, b, points of great depth, and therefore of great erosion.

portionate to its thickness. Thus, on any irregular surface of country, the cutting power of a glacial sheet will be proportionate to the depth of the ice above each part of its surface. Let us take the case of a section of the ice such as is represented in Fig. 11, which is supposed to be at right angles to the general course of

the flow of the glacier. What we know of the Greenland glacial envelope justifies us in supposing that the surface of the ice, *a a*, would be approximately horizontal, and that the rate of ice flow in the valleys, *b b*, would be quite as great, or perhaps greater than on the intervening ridges. It is clear, therefore, that the valleys, *b b*, would be more rapidly excavated than the ridges. Moreover, the subglacial streams would follow the lines of the valleys, and add their great eroding forces to that of the ice. We are forced to believe that these streams flow under very different conditions from streams in the open air. The massive ice above them is too thick to form arches, and must press upon them with great force, unless, as must rarely happen in continental glaciers, there should be some line of escape for the water to the upper limits of the ice. In a section of a mile in depth the weight of the mass would inevitably close all the incipient fissures at the base, for the crushing strength of ice is not sufficient to withstand such enormous pressure. So it seems necessary to conceive subglacial streams, such as the Greenland glaciers show us, existing beneath our old glaciers, driven along by the weight of the ice as well as by gravity. If this were the case, such jets of water, armed with a full charge of detritus, and urged forward in a paroxysmal fashion by the varying pressure that drove them on would have had a scouring and abrading power of which we have little example in our ordinary experience.

Some of the most peculiar effects that arise from the action of glacial ice are due to its power of moulding itself and its underrunning streams to the surface over which it moves. A river can only cut an inclined plane from its head to its point of discharge into the sea. It may cut sideways in this course, and thus change the position of its valley to a considerable extent. But a glacial stream can descend into and emerge from deep basins. More than that, it can excavate cavities of great depth across its line of flow. Familiar instances of this work occur in all glaciated countries when we enter far enough into the field they once occupied to get where there was a considerable depth of ice. On the southern face of the North American ice sheet we find no deep basins, but as soon as we penetrate a hundred or so miles away from the front, where the ice field was deeper, we find a great number of such cavities. The lakes of Switzerland, those of New York and New England, are good and familiar instances of this work. On a larger scale this work is indicated in the great lakes of the central parts of the country, and the numerous excavations that divide the northern part of the continent into a sea of islands.

It should be noticed that the work of glacial excavation is more absolutely

governed by the hardness of rocks than is that done by running water. A river cuts under very different conditions: a soft rock which is above its level may waste rapidly, but as soon as it is planed down to the level of the water the work of the river ceases, nor can a river erode a great ways laterally; the laws of its current movement tend to keep it to a tolerably straight course, and any bend hampers its work. But beneath a glacier there are no such limitations; every line of weakness is searched out and probed to its bottom. To a certain extent, the deeper the excavation thus made, the more energetically the ice acts, because of the increase of its thickness: lateral surface movement and the motion of the ice in the direction of its flow tend to keep the surface level, and the excavation deepens more and more rapidly, until the ice becomes clogged by the steepness of its walls, or the size of the excavation makes it impossible for the surface of the ice to keep its level. Then the wearing of the depression will go on no more rapidly than the erosion of the rest of the surface. In this erosive work the ice is greatly aided by the underrunning water of the glacier. These streams, which were clearly very powerful and extensive, would tend to scour out the waste as it was ground fine, and bear it away towards the margin of the glacier. That those lake basins were so excavated is pretty well proved by a number of facts. In the first place, they are limited to the regions which have certainly been extensively glaciated. Some great basins, such as those occupied by the lakes of Central Africa, have doubtless been made in other ways; but whenever we find the long narrow basins, such as abound in New England, though their forms are much masked by drift, we may be pretty sure that we have the results of glacial work. Now, it is a remarkable fact that, generally speaking, the length of these lakes coincides closely with the lines of flow of the ice, as shown by the glacial scratches. In North America, especially in New England, these lines generally run from a little west of north to a little east of south, the central ice constantly pushing the mass a little outwardly to the seaward. So closely is this general course followed that it is said the Indians in thick weather used these lines as a means of telling the position of the north. The glacial basins of this region have their axes closely coincident with the path of the glacier, as indicated by these striæ. The lakes of New York also show this course, but it is beautifully apparent in the directions of Lake Champlain, Memphremagog, and a host of lesser sheets of water. It would, however, be incorrect to take these lakes as sufficient measures of the eroding work of the glacier during the last ice time.

In the first place, they have been greatly diminished in extent by the waste that has been heaped into them. When the ice went away the streams of water had their free sweep of vast masses of débris left on the surface. This waste they hastened to heap into the recent depressions, and with such effect that a large part of the old lakes have lost more than half their depth and area thereby. Then, after the ice passed away, the plants reoccupied this region, and peat swamps began to encroach upon the lake areas, rapidly closing in their borders towards the central deeper water. Moreover, it was only when the excavation had no outlet, or where the dam of detritus lay across its mouth, that a lake has been formed at all. But the observer should go into the rocky fields of New England, and walk across a district where he may see the form of the underlying rocks, and there get an idea how irregular is the wearing that is done by the ice. We see there that the whole surface is warped into ridges and furrows from a few inches to a good part of a mile in width; the flexures are laid one upon another, like the lesser waves on the greater in a storm-swept sea.

Along the coasts of the glaciated zone the fiord indentations and outlying islands give also a good impression of the irregularity of the glaciated surface. The character of them is well shown on the coast of Maine or that of Norway. The fringe of islands, the deep indentations of bays and inlets, are but the remains of the irregularities produced by glaciation and made evident by the level line of the sea.

These irregularities are always less pronounced than they were when the ice left them, for the reason that the sea tends always to reduce the variety of outline of a shore by heaping all the waste that it bears from the headlands or obtains in other ways into the bays of the coast, and by planing down the harder rocks. Although generally these excavations made by the ice lie with their major axes in the direction of its flow, there are conditions where this is not the case. A familiar illustration may be found in the trend of the excavations in Boston harbor and city. The general direction of this basin is northeast and southwest, while the course of the ice was from northwest to southeast, so the direction of the excavation is nearly at right angles to the movement of the ice. This has been brought about in the following way: the region in which the trough lies is a great synclinal fold or mountain down-curve. The beds that filled the depression were of materials much more yielding to the ice action than those upon the northwest and southeast. The former are clay slates, conglomerates,

and associated rocks; the latter, syenites and other similar rocks of great hardness. So that, when the excavating forces of the ice took away the softer materials to a considerable depth, they left a basin having an elongation in the direction of the trend of the weaker rocks, and not in the direction in which the ice flowed. We may, indeed, lay it down as a general fact that when the ice cuts out an excavation in homogeneous materials the basin will be elongated in the trend of the motion; when, on the other hand, it digs out softer materials from the midst of harder rocks, the excavation takes the form of the softer rocks. These facts may seem to be matters of course, but the writer had to look some time before he saw them in a clear light.

This phenomenon is traceable on a small scale on the surface of some of our conglomerates where the ice has done its work. We find the hard pebbles which have been left projecting from the rock by the erosion of the softer matrix, showing the facts of shock and lea sides with great distinctness. A study of such glaciated surfaces is very helpful to the student of ice action. The varying hardness of the rock, due to the variety of substances of which the pebbles are composed, cause it to illustrate in miniature the effects that the ice exercises on a large scale over the continental surfaces.

Although such powerful work as we have just been considering is perhaps the most important part of the deeds done by continental glaciation there are many other important modifications of its work; among them we may mention the effect of their action upon mountain ridges, their action in general upon the preceding geography of a district, and their effect in transporting the detritus they have worn from the rocks over which they pass.

The action of ice upon the mountain ridges that lay in its path was very great. In a general way we may measure it by the profoundly worn character of all the mountains within the range of powerful glaciation during the last ice time. It is not certain, however, whether any form of glaciation could do much to wear away such ranges as the Cordilleras or the Himalayas. These peaks would probably, even on the most extreme glaciation, become the centres of dispersion of a glacial system, and as such would escape the action of the ice in a tolerably complete way. On the lesser mountains the glaciers certainly do very effective erosive work. Although the ice has less direct cutting power on their heights than in the valleys on either side, it is able to attack their peaks and flanks at great advantage on account of the exposed form of their slopes and the forward

pressure of the ice urged on by the weight of the mass behind. The energy of this movement is seen on the slope of the mountains themselves: they generally show what is called a shock and lea sides, or crag and tail as it is called by English geologists; that is to say, the side against which the glacier grinds is worn down to a relatively gentle slope, while the side opposite, or that away from the course of the glacier, has a much steeper slope. On the north side in many cases we find the débris swept away, while on the south the waste generally lies gathered under the hill in considerable quantities. Fig. 12 illustrates the difference between the preglacial outline of several hill-forms and that given by a moderate amount of glacial erosion acting upon the same elevations. These shock and lea hills abound in New England. They may be observed, on a small scale, in any steep mountain where the "roches moutonnées" are seen to be steep-faced southwards and gently inclined in the other direction.

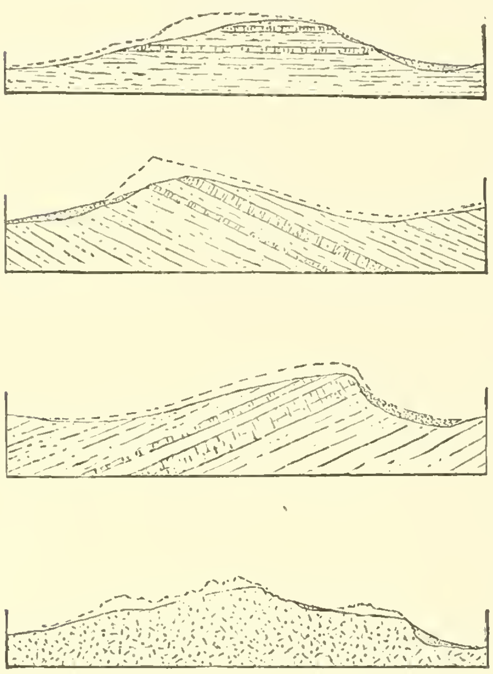


FIG. 12.
EXAMPLES OF GLACIAL EROSION.
The movement of the ice was from left to right.

If the mountain be composed of a peculiar rock that may be identified by fragments, we shall be able to trace the line of march for great distances. These boulder trains, as they are termed, are often of singular length and continuity. Very beautiful examples may be found in the Berkshire Hills; that at Richmond in Berkshire County, figured on page 45, is the most remarkable ever described. The trains of boulders, with a width of many rods, trail away for miles from the mountain whence they were rent. Many other similar cases may be found in New England, of which only one need be cited. In the town of Cumberland, in Rhode Island, there is a hill of some acres in extent composed of a peculiar titaniferous iron ore. The glaciers found this mass a tough nut to crack, and its surface was polished rather than rent by the ice, yet enough was torn away to build a train that can be followed for a score or more miles to the southward. During the Revolution, and again in the War of Secession, these iron boulders were gathered for the manufacture of iron; still they are traceable from point to point along the line.

We generally find, where boulder trains exist, that the fragments grow smaller and smaller as we get farther away from the parent mass. This shows us the essential difference between the carriage of boulders on the surface of a glacier of the Swiss type, and at the base of the ice in a continental glacier. Deposited on the surface of a glacier, stones may journey for an indefinite distance with but little waste; in fact, the conditions there are very favorable for their preservation: but at the base of the glacier, where all the waste lies near the floor of the ice sheet, the conditions bring about the speedy destruction of the embedded materials; every step forward in the march of the ice causes a certain amount of wear. There is no means whereby the stones can mount to the surface of the ice. They are held down to the bed, and rubbed against each other and against the fixed rocks of the earth, so that they soon pass into dust and fragments, and are then borne away by the subglacial streams.

Under these conditions it is surprising that the detritus succeeds in making as long journeys as it often effects. Some of these excursions are certainly far reaching. Perhaps the best proven case of such carriage is found in the pebbles of hypogene rocks, granites, etc., that lie over the surface of Southern Ohio. There can be no doubt that these pebbles have been brought from the Laurentian mountain system in Canada, and the distance that some of them have travelled is not less than five hundred miles, making a descent and subsequent ascent of several hundred feet. The greater part of these pebbles are very small, and exceedingly worn by what seems to have been the action of running water, yet the condition of the beds in which they occur shows that they have not been worked over by streams since the glacial period passed away. This rounded and water-worn look, which is common to all the pebbles that have suffered distant transportation, seems to indicate that their carriage beneath the glacier was mainly effected by the action of subglacial streams.

It seems to be a general fact that the more rugged the surface of a country the less distance are the fragments transported. A rough surface, doubtless, operates so as to bring one fragment after another into actual contact with the rock surface below, and so aids the destruction of all the boulders.

The amount of débris carried forward to the face of the ice-sheet is enormous. In Ohio the detrital sheet may be estimated at not less than thirty feet thick over the whole surface of the State, or as much as fourteen hundred cubic miles, or much more than the débris in the Mississippi delta. The worn and shrunken

terminal moraine of Long Island, N. Y., is probably not less than five hundred feet thick, and contains at least a hundred and fifty cubic miles of waste. Including Block Island, Martha's Vineyard, Nantucket, Cape Cod, and the George's Shoals, we may reasonably compute that the New England terminal moraines contain at least five hundred cubic miles of matter. If we take the glacial débris scattered over the surface of New England, which will, I believe, average at least twenty feet in thickness, we shall have a total mass of seven hundred and fifty cubic miles of glacial waste derived from a surface of not over sixty thousand square miles of area, for little or none of this débris came from beyond the St. Lawrence River. This mass is equal to a mountain range five hundred miles long, two miles wide, and a mile high. It is more than the whole mass of the White Mountains, and represents probably more waste than would go by water erosion from the surface of New England in half a million years. Estimating the sheet of glacial débris now on the surface of the mainland, and excluding all the terminal moraine matter that lies beyond its shores, we can safely call the glacial waste of New England at least twenty-five feet deep. I have come upon this basis of estimate after a good deal of inspection of its surface, and by averages taken at many points. It may be much in error, but the mistake, if it exists, must be in the underrating of the thickness. Now, to remove this thickness by water erosion from the surface of granitic rocks would require more than a million years. Let us allow that the rate at which a glacier moved was three hundred feet per annum, and call the distance travelled by the glacier from north to south in doing this erosion an average of two hundred miles, then the ice would pass across the surface of this district in about thirty-four thousand years. It may be assumed that the rate of motion of the débris at the base of the glacier is as great as that of the ice itself. It is true that some of it may lag behind the ice, but this will be far more than compensated for by the great amount of waste carried out by the subglacial streams, which move onward at a far greater rate than the ice itself. If, then, the whole of the loose waste on this surface during the glacial time moved forward at this rate, in something like thirty thousand years all that we now find here would have moved off and been replaced by new materials. This very rough computation would seem to show that the rate of erosion in New England must have been very much greater than that effected by flowing water. It would make the rate of glacial wasting as much as one foot in one thousand years, while the average rate of wasting of the Mississippi Valley is one foot in about seven

thousand years. But the half at least of the present waste in the Mississippi Valley comes from limestones and other rocks that wear under the action of the water several times as fast as the granites of New England. So we must allow that this estimate has yet another likelihood of being too low for the truth. There is thus a reason to believe that the regions that are under the mantles of the glacier are more effectively worn down by the action of the solar forces working through rain or snow than the lands that are exempt from ice action.

The action of glaciers of the continental type upon the general geography of the regions they affect is very different from that of running water. While ice action is limited to the Swiss type, while it acts only as local streams in the existing valleys of mountains, it operates only to cut deeper the valleys and to widen their troughs. When it operates on the broad surface of a continent it becomes to a much greater extent an engine of change. This change in the geography of a country is accomplished in two very different ways. In the first place, the ice carves for itself a new geography, and, in the second place, it leaves masses of waste on the surface of the land that clog the drainage and turn the streams in diverse ways. The great American glacier of the last ice period will supply us with numerous instances of both these actions. Professor Newberry has recently shown it to be probable that the drift of the last glacial period clogged the drainage channel which once extended from the Great Lakes to the Hudson, thus directing a vast system of waters to the more northern channel of the St. Lawrence. It even seems probable that the path of this last-named great river may owe its existence to the action of glaciation operating in the last or perhaps in the several last glacial periods. There is no other way of explaining the existence of that system of waters so well as by this means.

A very little more cutting by the ice sheet or a slight change in the incidence of its force would have broken down the low barriers that intervene between the St. Lawrence system of streams and the more southern drainage systems of the continent. The Lake Champlain chain of depressions, extending from the St. Lawrence to the Hudson, would require a lowering of only about one hundred feet to discharge its waters into the Hudson. The barrier between the Hudson and Lake Ontario is also low. Between Lake Michigan and the waters of the Upper Mississippi there is hardly any barrier at all. A further cutting by the ice of even twenty feet at that point would have led off the waters of a part of the Great Lakes to the Mississippi. The St. Lawrence has a slight southern boundary, and is not likely to escape so easily in the next contest with the ice.

It is not only the St. Lawrence valley that owes much to the ice action of the last glacial period; many other of our American valleys are to a great extent the product of its action. The Hudson, though a broad mountain trough, has been greatly widened and deepened by the ice ploughs. The same is the case with the Connecticut, and in a lesser degree with all our New England valleys. Their shape and direction were, doubtless, given by the streams of molten water, but their slopes have been profoundly modified by the mightier forces that the ice brings to bear.

Some of the most interesting results of glaciation are found in the varied aspects of the waste which it has left upon the surface of the land. The peculiar forms that this waste had given to it by the circumstances of its origin and the various conditions that have been impressed on it by the changes that flowing water brought about, make its phenomena extremely puzzling to the geologist. We have spoken of glacial waste as if it had one common character; in fact, it is of the most varied composition, differing widely in the cases of local and continental glaciers. Limiting ourselves to continental glaciers, we may first consider their terminal moraines. These are not the heaps of stones set across narrow valleys, such as our experience in Switzerland familiarizes us with, but are vast accumulations of a very different type. They are shown to best advantage on the coast of New England, in the remains of the great moraine that now persists in Long Island, Block Island, a part of Martha's Vineyard, the Elizabeth Islands, Nantucket, and a part of Cape Cod. Here the glacial waste was deposited, mostly under water, in the shape of stones, gravel and mud, somewhat rearranged by the action of the sea that swept the waste to and fro over the bottom where it was accumulated. On top of this mass at certain points, as in the northeast face of Martha's Vineyard, there are some patches of waste that were perhaps laid down after these lands were above the surface. But, as a general thing, they are stratified deposits very unlike the Swiss moraines.

Along the shore within this belt of stratified terminal moraines we have a main-land that was depressed during and just before the glacial period to a depth that increases from New York, where the depression did not exceed forty or fifty feet, to Boston, where it was not over ninety to one hundred feet, and to the coast of Maine and the region of Lake Champlain, where it was from two hundred and fifty to four hundred feet. Proceeding farther north, we increase the magnitude of this surprising depression, the cause of which we will discuss further on, until we find in Greenland evidence of a sinking that exceeded a thousand feet. In this belt

of submerged land the waste left by the glacial period was subjected to great changes, in the first place by the action of the sea upon the easily worn glacial matter, and later, after the sea passed from it in the re-elevation of the land, by the return of the streams of running water. Still higher within the country we have the glacial waste as it lay when the glacier left it, except for the changes that the flowing waters have brought about.

Let us begin with the waste as it was left by the glacier, for, puzzling as are many of its features, it is less difficult to understand than the other varieties of "drift" that come from the metamorphoses that running water brings about.

The formation and disposition of the waste beneath a great continental glacier was guided by laws that we cannot readily understand. We cannot penetrate to the place where the eroding work is at its height in any glacier, so we are driven to inferences as to what goes on there. There can be no doubt that during the depths of the glacial winter every part of the ice was underlaid by a more or less deep sheet of detritus that was soldered into a mass by the ice. As this lower part of the ice was driven forward, it kept tearing off new fragments from the rocky bed. At certain points we can find where a great fragment — hardly deserving the name of boulder, for it is not yet rounded — may be seen near the point where lies the scar made by its separation from the parent rock. Above it may be a score of feet of waste that is more rounded and ground, from its longer journey. Even a few feet from its point of origin this newly riven mass will be found underlaid by other rocks derived from farther away, which have been forced beneath it. This seems to indicate an incessant churning over of the glacial waste as the sheet moved on. It is to this constant overturning of the detritus that doubtless is due much of the rounding and polishing of the pebbles it contains.

We can imagine this mass of ice, stones, sand, and clay, all commingled together by their rough travel, settling on to the surface of the land when the ice went away. This process of retreat had a very important influence on the waste. It was not immediate, like the melting of the snows of winter; it must have occupied many thousands of years. Where the surface was level and remote from high mountains, the backward melting seems to have occurred in a rapid fashion, geologically speaking; but in the mountains it was slow, and even in the lower lands was attended by one or more advances, in which a thinner ice-sheet passed over the waste left by the greater glacier that preceded it. This movement of relatively slight glaciers would tend to thrust forward to the ice front the thick mass of

débris which lay upon the surface, the work of the heavier ice, and leave the ground nearly cleared when the thinner ice slowly disappeared. This action is best seen in the more mountainous districts, where the continental ice gradually gave place to local glaciers, which maintained themselves for many thousands of years after the main mass of the ice had departed. In New England the whole range of the Berkshire Hills and the Green Mountains, the White Mountain group, even small mountain masses, such as Wachuset in Massachusetts, set up these independent centres of glaciation, and filled their valleys with ice streams long after vegetation had crept back to the valleys, and the lower lands had acquired their present aspect. The smooth and bare character of the mountain ridges and other uplands of New England can be accounted for in this way. After the ice streams became too thin to have much crushing and eroding power, they still retained enough strength to wear out and remove to the lower lands the waste that the greater continental glacier had left upon the hills.

In this way, during the successive and numerous advances and retreats of the thinner ice, the original boulder clay or till — that is, the mass that lay at the base of the continental glacier, and was left upon the surface as it melted away — has been to a very great extent worked over and changed to other shapes of drift.

The original boulder clay of New England is practically limited to the upland regions, or those above the line of submergence, but even there has nothing like the continuity which is seen in the level country of Northern England or of Ohio, where the ice went away promptly and without any returns. Good examples of it are found along the shore from Portsmouth, N. H., to Newport, R. I. This angle of the coast was, as a whole, more promptly and permanently deserted by the ice than the other parts of New England, and so a great deal of the waste lies there in an unchanged form. Its unstratified structure is seen in Plate XXIII., contrasted with the bedded arrangement of the more modern terrace-drift.

The original shape of the till in this district seems to have been that of a discontinuous sheet from ninety to one hundred feet in thickness, a confused mass of stones of all sizes and shapes, all generally much worn, cemented together in a very compact fashion by clay mingled with sand. No distinct stratification is visible in the mass, but here and there are patches of sand, and sometimes the boulders are grouped in horizontal lines. During the time in which the land was depressed

below the level of the sea, the tides washed over this part of the boulder clay, and cut the most of it away, bearing the waste to the sea or leaving it strewn along the shore in complicated forms of secondary drift. The rest of the boulder clay is found in positions where the sea could not get access to it. Such protection was best afforded by the lesser arches of rocks, the larger "roches moutonnées," that abounded in this district, perched on those elevations that rose above the level of the sea. Patches of the till have remained essentially unchanged since the ice left them. The sea cut under their edges, and the action of sub-aerial erosion moulded their upper surfaces until they assumed the exquisite arches that originally marked the surface of this region, and still occasionally remain, despite the marring hand of man. Plate XXIV. shows the form of some of these hills near Boston. In height they seldom reach three hundred feet. Not infrequently this boulder clay survived without the protection a pedestal of solid rock might furnish, but a large part of it that remains in its original state rests upon the rock ridges. There are some scores of these known to me between the mouth of Narragansett Sound and the entrance to the Merrimac River, and they occasionally occur in the inland districts of New England. It may be well to note, however, that there is considerable difference of opinion in regard to the cause of accumulation and origin of form of these arched hills.

Even more conspicuous than the arches of boulder clay are the table-lands of drift that are found at lower levels along this shore. Terrace-like deposits of drift occur along the whole coast from New York to Nova Scotia, but to the north, where the ice lay longer close to the shore line, and the depression was greater, they are less conspicuous than in the region from Boston southwardly. Where best shown, these terraces consist of broad benches at various levels, from near the sea line to the height of about eighty feet. The lower are the most distinctly marked, for there the sea seems to have worked for a longer time, and therefore more effectively. The surface of these terraces is smooth and essentially devoid of boulders. We notice that the fences upon them are not composed of stones, which elsewhere in New England are generally used for boundary walls. The interior of the terraces consists of more or less irregularly stratified sands and pebbles, all showing the action of running water. The small boulders they contain have, through this water action, generally lost the somewhat angular character and scratched surfaces they have in the boulder clay. On the edge of these terraces we have a steep escarpment leading down to the sea level or to the next

terrace below, showing the cutting power of the tides in the period just following the elevation of the land. At a few points the terraces, especially those about

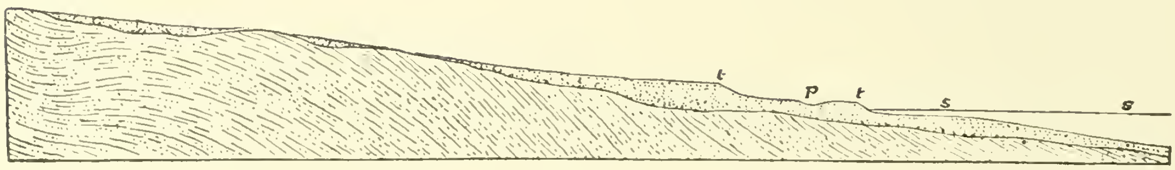


FIG. 13.

DRIFT-TERRACES ON THE SEA-COAST.

t, t, former ocean-levels. s, s, present ocean-level. p, depression on surface of terrace.

twenty feet above the sea level, show us peculiar pit-like depressions sometimes a hundred feet wide, and nearly as deep as the terrace is high. These are often grouped together, four or five pits being adjacent to each other. These depressions exist all along the shore. They are well shown in the northeast corner of Aquidneck Island, R. I., or on the shore line of Quincy, Mass., near the mouth of the old canal. After a good deal of inquiry, they seem to me to be most easily explained by supposing that the second advance of the ice, which clearly took place at about the time these terraces were forming, sent its tongues of ice down into the fiords and bays, and furnished small icebergs, which grounded in the water where the marine tides deposited rapidly their sediment. Buried in this terrace deposit, these icebergs would melt slowly, and time enough might elapse before they disappeared for the water to coat them about with sand, and so insure their preservation among the sediment until the sheet of waste was built out beyond them. When they melted away the place they occupied would remain as a cavity. Something of this sort on a small scale may be seen in our rivers when they drive out their ice in the spring-time. Heaps of ice are often built into the sediment that the flood deposits in the streams, and, melting, leave little pits to mark the place where they lay.

We have alluded to the second advance of the ice. We recognized here a moving forward of the ice that brought local glaciers into the upper waters of all the great fiords of this section of our coast; there may have ,been several such readvances, but only the last of these slight relapses of the glacial conditions are recorded here. This second advance left some moraine heaps much more like the Alpine moraines than anything else along this shore. At certain points this

moraine matter lies upon the terraces, and it is often imposed upon the patches of boulder clay.

After the formation of the last and lowest terrace there was a general uplift of the shore, and then the conditions of this country came into much their present shape. The sea set about building another terrace, that still lies below its surface, and though the level oscillated up and down in an uneasy fashion for some time, no change of more than ten or fifteen feet has occurred in the regions between New York and Maine. All the subsequent changes, the filling up of the fiords by salt marshes, the shallowing of the soundings in the part of their basins still possessed by the sea, though most interesting phenomena to the student, are beyond the limits of the class of the conditions brought about by the glacial period.

We will now turn to the drift not included within the belt of submerged land, and therefore beyond the limits of the marine forces. Its character has been determined by the action of running water, and the influence of vegetation. It is evident that the glacial period was a time of great rain-fall, and that this rain-fall continued large, even after the ice had begun to move away. In the opinion of some geologists the disappearance of the glacial sheets was the cause of a great deal of washing to and fro of the drift; but this is not very likely for the reason that even if the glacial sheet had been but a few thousand years in wholly melting, it would not have made a larger contribution to our streams than they could readily carry away. Within the limits of their flood basins our rivers are able to take away many times as much water as now falls upon the land, if it were given to them with the steadiness with which it must have come from the melting of the ice sheet. The principal cause of the great effect of the rain-fall on the drift was the confused state of the drainage of the country. Although all the main valleys which determine the place of the rivers were in existence when the rivers were re-made, yet they were clogged by masses of drift which had to be much worked over before the streams took their present courses. In every little mountain valley and on every plain a host of small ponds and marshes, that exist no longer, were formed. As these burst from time to time, they formed great floods that poured down into the next reservoir, perhaps also to burst its retaining walls. Now and then it happens that some of the few remaining slightly walled lakes are swept away in this fashion. The most of this work, however, has long been done, and in the process a large part of the waste the glacier left behind it has been shifted about and sorted by water. Most of this waste has been carried

into the main river valleys, where it has been ground up and sent as fine detritus to the sea, or it has been left in the terraces along the streams, where it awaits the to and fro motion of the stream till it shall again take up its journey to the sea. The Connecticut and its tributaries have some score of cubic miles of this waste in their terraces, and the altitude of these terraces shows that much more than that which stays has gone on its way to the great reservoir of the deep, whereunto all things tend.

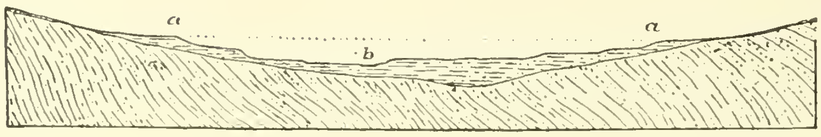


FIG. 14.

RIVER-TERRACES.

a, a, level to which the valley was once filled with fine stratified drift.
b, present river channel.

The drift that remains in the inland districts of New England in the shape in which the glaciers left it consists of irregular heaps of waste, which were pushed about by the shifting of the ice in its successive advances and retreats. It thus has at some points the semblance of terminal moraines, but it differs from the typical moraines of Switzerland in many distinct features. These successive movements of the waste have given a chance for the mud and fine sand to work out of it, until it is often left as a mass of loose stones, with little of the cementing matter so characteristic of the boulder clay. Again, all the stones of the heap are more or less rounded, and the scratches generally wanting, while the Swiss moraines are largely composed of angular boulders, and these often much scored. At times the ice tongues pushed up a deposit of sand or mud, and made a moraine-shaped heap of these substances, which could not be built into moraines in the ordinary way. At other points we find very long ridges of assorted glacial waste, sand, pebbles or clay in a stratified form. Sometimes these ridges stretch for miles across the country. They have received the name of åsar in Norway and Sweden, kames in Scotland, and eskers in Ireland. No sufficient explanation has yet been given of their origin.

It seems likely that this class of long, more or less stratified ridges includes several different sorts of glacial deposits. In some cases they are clearly local moraines. The best instance of this division of the class that can well be found lies in the valley of Mill Brook, on the south side of Gardner's Mountain, to the

northeast of the village of Lisbon, N. H. In this valley, about five miles from its mouth, we have a set of continuous ridges, the most conspicuous of which is about a mile and a half in length, and from ten to twenty feet in height, with an average width of about one hundred feet. This ridge is irregularly continuous. Its upper surface is occupied by the main road that passes through the valley, and the summit is so sharp that it barely gives sufficient room for the way. At three or four points the ridge falls away to the general level of the valley; these spaces are never more than a few hundred feet in length, generally, in fact, much less than this. The history of this ridge seems to have been as follows: during the retreat of the ice the valley where it lies was for some time occupied by a local glacier. Into this glacier the boulders, gravel and sand were swept from the higher slopes, furnishing materials for a central moraine. The slope of the valley being very uniform, the retreat of the ice was so equable as to build this long terminal moraine. It affords excellent evidence that the retreat of the ice was singularly uniform, and not at all paroxysmal, as some have supposed it to have been. Although this is a singularly good example of a continuous moraine, there are abundant similar deposits in our New England valleys.

The attentive observer will remark that much of the drift on the upland areas of New England is more or less distinctly arranged in belts having a south or southeast direction. Each of these belts consists of many broken but more or less parallel ridges, composed of irregularly stratified drift, with occasional masses that do not seem to have been subjected to the action of running water, for they exhibit no stratification. Between these belts are intervals of many miles in width, where the drift is scanty and not accumulated into distinct ridges. Conspicuous

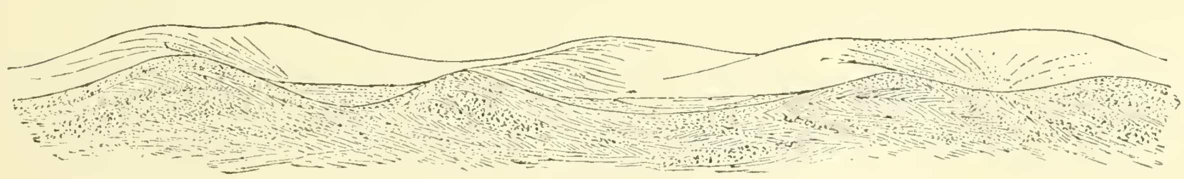


Fig. 15.

Outline View and Section of a Group of Kames.

examples of such series of kames may be found from Andover to Melrose and from Concord to Dedham and beyond, in Massachusetts, and at many other parts of this

State and Maine as well as abroad. They are often variable in size and continuity, sometimes almost disappearing, then rising again a little farther on in fine development. Broad sand plains occasionally take the place of the irregular ridges, and ponds caught in the undrained hollows among the scattered deposits frequently mark the course of a kame series across the country. In breadth, the belts reach one or two miles; in length, some have been traced over one hundred miles.

It appears likely that such deposits as that just described cannot well be regarded as belonging to the class of moraines, and it may be long before we understand the method of their formation.

We cannot hope to restore a perfect image of the glacial sheet during its time of activity or decline. Its conditions are too complex for the mind to grasp, and the record is too fragmentary for restoration. The most we can hope is to patch out the fragments of fact that are left to us with reasonable conjecture, keeping always close to analogies presented to us by the existing ice fields of other lands. It is not the least of the good features of geological science that it constantly calls on its votaries for the exercise of that imagination without which no interpretation can be carried very far.

There is no field that offers so much to the student as this work of explaining the glacial history of any district; but the work demands the most skilful labor that can be brought to it, and the utmost patience in the inquiry. If pursued with method and with patience, it is sure to bring before the student a vivid picture of the strangest conditions that the past has to reveal.

CHAPTER VI.

THE ORIGIN AND NATURE OF GLACIAL PERIODS.

THEORIES OF GLACIATION. — HEAT OF STARS. — EFFECTS OF THE ATMOSPHERE. — ECCENTRICITY OF THE EARTH'S ORBIT, ETC. — CROLL'S HYPOTHESIS. — ACTION OF OCEANIC STREAMS. — CHANGES IN THE SOLAR HEAT. — CHANGES OF GEOGRAPHICAL CONDITIONS.

BEFORE geologists were awakened to an understanding of the work of glacial periods in the earth's history, they had already been brought to the consideration of the climatal changes of former geological periods. Early in the history of that part of geological science termed palæontology, the fossils in the rocks made it clear that the climates of the earth had not always been what they are at present, but had undergone changes of a startling nature. In the first years of this century the fossils found in high latitudes near the Arctic Circle showed that the life there had been at times almost tropical in its character. So, before glacial periods were known to have existed, these geological proofs of warm periods had begun to turn the attention of naturalists to the causes that could bring about revolutionary changes of climate. As soon as the writings of Agassiz and others had shown the former wide extension of glaciers, attention began to be more intently turned to this question, and the interest in the matter has been still further revived as the evidence has been collected that enables us to assert that glaciation is a recurrent and not an isolated feature in the earth's history. The various hypotheses to account for changes of climate afford us some of the finest instances of the proper use of the imagination in the interpretation of nature. We will, therefore, briefly review them, and select from them the theory that seems best to accord with the facts.

The first theory brought forward to account for glaciation was that the earth, having been originally in a fiery state, had in cooling passed from a condition of universal warmth to a more and more frigid state, until the present conditions were attained. This is the least tenable of all the theories, for it neglected the now evident fact that there had been changes from cold to warmth and back again to cold. However, as it was invented before the existence of glacial periods was suspected, it long commanded a general assent, and was the opinion that held the ground until near the middle of this century.

About 1830–40 the researches of Poisson and several other French physicists made it clear that the heat of the earth's surface came almost altogether from the sun and the celestial spaces, the heat of the earth's interior having almost nothing to do with the temperature of the air. We have already called attention to the fact that only about one half of the heat that falls upon the earth's surface came to it from the sun, the rest coming from the other bodies in space. At this time the motion of our solar system through the regions of space had just been perceived; it was, therefore, quite reasonable for Poisson to make the suggestion that in this way our solar system might, from time to time, come into closer neighborhood of stars which from their size or propinquity would give our planets a much higher temperature than they now receive. This seemed a very reasonable view, and, indeed, it cannot well be questioned that if one half the heat that reaches the earth's surface comes from the stars, it is likely to be warmer near an aggregation of these suns than it is where we are now. But the searching inquiry given to this question by Mr. William Hopkins has made it clear that while, in the course of events, the solar system may penetrate into regions of such diversity of temperature as to affect the climate of its planets, it cannot have produced the changes such as the geologist is required to account for. We will not follow further this curious theory of Poisson, of which we have given the bare outline, though, as a speculation, it is well worth more attention than has been given to it.

Next among the important hypotheses we have that which was so well expounded by Sir Charles Lyell. In this he developed the well-known influence of land and water upon climate. This influence had long been recognized, though to this day its effects are greatly misconceived. Lyell showed that if all the land were accumulated around the poles, and all the sea about the equator, the earth would have a very different climate from what it would possess if the reverse conditions occurred. There is no doubt that such would be the case; but the learned

author failed in this instance to be guided by the strict rules of criticism that so generally have made him the safest guide for the student. The occupation of the whole equatorial belt by land would tend to lower, not to raise, the temperature of the high northern regions by destroying the equatorial current and its branches, the several poleward-setting streams. The accumulation of land about the poles would have essentially the same effect; while it would admit of the existence of an equatorial girdling current sweeping around the earth always under the same parallels, it would offer no barriers to direct this current towards the poles, which is the first condition of having the regions of high latitudes at all habitable for life. Moreover, if such changes as Lyell's hypothesis supposes were competent to effect great changes of climate, the theory would be open to the absolute objection that it does not accord with what we know of the history of our continents. All the evidence points to the conclusion that the land masses have been, from the dawn of geological history, distributed much as we find them at present. Certainly in the last glacial period there was no such utter change of the relations of the continents as this hypothesis requires. So, while retaining the conviction that possible changes of the shape of the lands, by modifying the course of ocean currents, have greatly affected the climate of the earth, we cannot allow that the lands and seas have ever changed places in the fashion that Lyell's hypothesis requires us to suppose. We can readily perceive that any geographical change which should admit the North Pacific Gulf Stream into the Arctic Sea, or exclude the Atlantic Gulf Stream from it, would bring about the most profound alteration in the climate of the Northern Hemisphere, and even extend its effects to the Southern Pole, and such changes are easily within the limits of geological accidents. There is serious danger that the disrepute that the Lyellean hypothesis has fallen into may serve for a while to divert attention from the real importance of even slight geographical changes to the climatology of a country.

The researches of Tyndall and many other physicists on the laws of radiant heat have made it clear that the atmosphere, including in the term everything that enters into the gaseous envelope of the earth, has a most important effect upon the temperature of the earth's surface. The addition of a little vapor of water, or of carbonic acid, or indeed almost any of the substances which we can conceive as entering into our atmosphere in the ordinary course of nature, would materially add to its power of resisting the radiation of heat, while they would not hinder the entrance of the heat that comes from the celestial spaces. The elaboration of this

idea, which we owe substantially to John Tyndall, undoubtedly supplies us with a knowledge of the agency that is capable of the most important effects upon climate. Our atmosphere, at any given time of our earth's history, depends upon a most complicated and necessarily variable interaction of many diverse causes. The oxygen and nitrogen gases, that have the least effect in retaining the heat of the earth, are probably the most permanent elements of the air; the water and the carbonic acid gas, which do the most effective work, are dependent on conditions that cannot be perfectly uniform. Within a few miles of the earth's surface, stored in our limestones, coals, and other forms of carbon, lie some thousand times as much carbon as the air contains, all of which has come from the air to the rocks, and may return to it. At no time can any large part of this mass of carbon have been present in the atmosphere, at least since the dawn of life on the earth's surface. But every volcano discharges a large amount of this substance into the air, and every plant or animal that is buried in the earth takes something from it. If the escape of this gas through the volcanoes and other points of discharge at any time exceeds the amount taken from it by plants and buried in coal-beds, limestones, or other carbon-bearing strata, then the capacity of the atmosphere for retaining heat will be increased, the moisture in the air will be added to by this increase of terrestrial heat, and this in turn will increase the heat-retaining power; so, by doubling the amount of carbonic acid gas, a sensible augmentation of the general heat of the earth's surface would be readily brought about. The range of this action is, however, quite small, for the tolerance of organic life to carbonic acid gas would not permit the present amount of the gas to be very much increased without a destruction of the higher forms of that life.

It cannot be doubted that we have here a true cause of wide-spread change of climate, but the change that it can bring about is one that would give warmer rather than colder conditions. No further reduction of the carbonic acid now present in the earth's atmosphere seems possible, or, if occurring, would be likely, on account of its small amount, to affect the conditions of temperature. Yet any great outbreak of volcanic activity, such as seems to have taken place in the Cordilleras of North and South America during the last stage of the tertiary period, when for a time the volcanoes from the Arctic to the Antarctic Circle appear to have been in extreme activity, might at once surcharge the air of the earth with vapor and carbonic acid gas, and so profoundly affect its temperature conditions, until the counterbalancing agents, the plant and animal life, had done their work

of bringing the gases again into the earth's crust in the form of coal, bituminous shales, or limestones. Although, at first sight, these changes do not seem likely to help our understanding of the glacial period, we shall hereafter see that every cause that can increase the general temperature of the earth is helpful to us in our effort to understand the history of this great problem.

The next hypothesis in the order of its development is that brought forward by Mr. James Croll, a geologist to whom perhaps, more than to any other of the living students of the earth, we are indebted for clear and penetrating conceptions of the order of events on our earth's surface. Mr. Croll's explanation carries us back to the conditions of the celestial machinery, and seeks to account for the alterations of terrestrial temperature by means of well-known, but hitherto imperfectly conceived changes in the position of the bodies in our solar system. Although Mr. Croll's theory is set forth with exceeding clearness, it yet involves considerations of phenomena that are not readily grasped without an extended and careful presentation. The reader will be repaid for his pains, however, for there is no theory in geological science that is made more charming by the sustained imagination that characterizes its many steps.

In the first place, we must note once again the fact that the earth's heat comes in larger part from the sun, that the stellar heat only serves to raise the general temperature of space so that the heat of the sun can do its appointed work on the surface of the earth. It should also be clear to the mind that the variations of the seasons, and almost all the peculiar effects of the irregular distribution of heat on the earth's surface, are due to the changes of position of the earth in its passage around the sun, each pole in its period of summer being turned towards the sun. Further, that this orbit of the earth around the sun is not circular, as it might be if the earth were the only companion of the sun in the solar system, but an irregularly elliptical figure due to the pulling of the earth by the attraction of the planets, an attraction mainly exercised by Jupiter and Saturn. Furthermore, the place in this orbit in which the earth receives its winter or summer is subject to a constant change, owing to what is called the precession of the equinoxes. At present, as in the second diagram of Fig. 16, the Northern Hemisphere receives its summer exposure when it is farthest from the sun, and its winter when it is nearest to that source of heat, while the reverse is the case in the Southern Hemisphere. In a few thousand years these conditions will be changed, the place of the seasons having crept around the orbit until the conditions are reversed, as

in the first diagram. We may add to this conception that the major axis of the earth's orbit, that is, its diameter of greatest length, is constantly changing its place, as the association of the superior planets alters. It slowly revolves through the heavens, and so diminishes the length of time required to effect the change of our winter of the Northern or Southern Hemisphere, from the part of the orbit that is nearest to the sun to that farthest away from it. One other fact, and we shall have the outline of the physical conditions on which Mr. Croll rests his theory. The amount of the ellipticity of the earth's orbit, or the difference between its longest and shortest diameters, changes constantly as the planets pull together on the earth or antagonize each other's forces. The variation may be as much as eleven million miles, or about one twelfth the earth's mean distance from the sun.*

It was long ago suggested that the change in the eccentricity of the earth's orbit might have a material effect upon the condition of the seasons in the two hemispheres by shortening the winters and lengthening the summers, or *vice versa;* but closer inquiry has made it plain that a simple law of planetary motion compensates for the greater nearness to or distance from the sun. When a planet is nearest the sun it of course receives more heat, and when farthest from the sun less heat, in a given time. But the nearer it is to the sun the more rapidly it travels, and the farther away the slower, so that winter and summer receive the same proportion of heat whether the orbit be eccentric or circular. To apprehend this clearly, let us for the moment suppose the earth's axis of rotation to stand as that of Jupiter does almost, at right angles to the plane of its orbit. The great cause of our actual seasons would then be absent, and we should expect only an orbital change; a perihelion summer and an aphelion winter. In Fig. 16, the second diagram may be taken as representing this relation of the date of the seasons to the position of the major axis of the orbit. Summer would occur while the earth passed through the lesser arc, *abc*, near the sun; winter, while we travelled

* As these conceptions are not readily grasped by most minds, it will be, perhaps, advisable to give a simple way of illustrating the essential points of the problem. Take a circle of wire, say three feet in diameter, for the earth's orbit; impale on it a round apple to represent the earth, letting the wire pass through the seeds at right angles to the core; then holding the circle horizontal, tilt the core into a line 23° oblique to the vertical, and it will show the position of the earth's axis of rotation. Let the central point of the circle represent the place of the sun. Then let us suppose several forces of traction working on the apple from constantly varying positions about it. These will represent the attractions of the planets that serve to change the shape of the orbit. With a little management this rude contrivance will serve to show everything of importance connected with this problem except the precession of the equinoxes, but this conception the imagination of the student will readily compass.

over the greater distance, *cda*, far from the sun. But the quicker motion over the shorter arc would expose the earth in summer for a less time to the increased heat of the near sun: the slower motion through a longer arc would hold the earth during its winter for a greater time before the diminished action of the far sun:

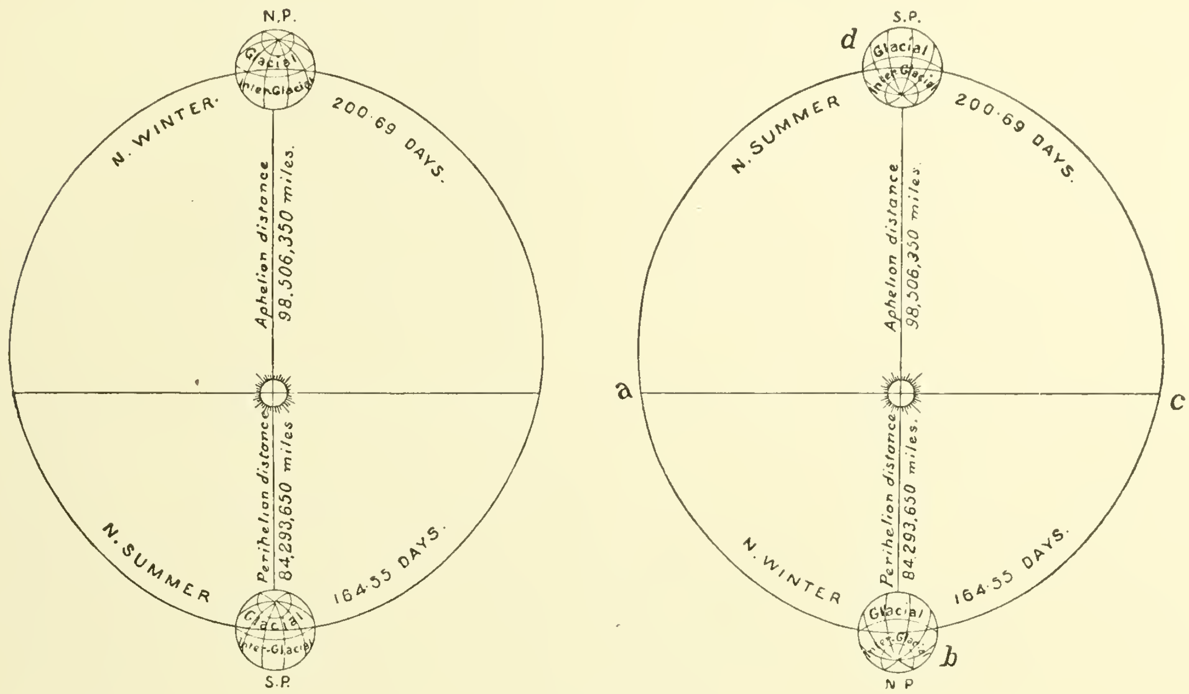


FIG. 16.

THE VARYING RELATIONS OF THE SEASONS AND THE DISTANCE OF THE SUN. (FROM CROLL'S "CLIMATE AND TIME.")

The right-hand figure shows the existing relation with the northern winter in perihelion.

and these differences in orbital motion and arc, and distance from the sun, are such as to balance each other precisely. As a result, the total amounts of heat received on the two sides of the equinoctial line, *ac*, would be equal. The temperature difference between this artificial and the actual condition of the earth was thought to be due entirely to the oblique position of its axis of rotation: therefore, this hypothesis of a difference of temperature directly caused by the eccentricity of the earth's orbit was abandoned by its originator shortly after it was suggested. For twenty years this suggestion seemed barren of all promise to the geologist, when Mr. Croll again attacked the problem. His results, at first scattered in a number of papers, have been by him collected in a volume on "Climate and Time in Geology." The following extracts from this treatise give, in as condensed a form as it is possible to put them, the substance of his theory: —

"There are two causes affecting the position of the earth in relation to the sun, which must, to a very large extent, influence the earth's climate, viz. the precession of the equinoxes and the change in the eccentricity of the earth's orbit. If we duly examine the combined influence of these two causes, we shall find that the northern and southern portions of the globe are subject to an excessively slow secular change of climate, consisting in a slow periodic change of alternate warmer and colder cycles.

"According to the calculations of Leverrier, the superior limit of the earth's eccentricity is 0.07775.* The eccentricity is at present diminishing, and will continue to do so during 23,980 years, from the year 1800 A.D., when its value will be then .00314.

"The change in the eccentricity of the earth's orbit may affect the climate in two different ways, viz. by either increasing or diminishing the mean annual amount of heat received from the sun, or by increasing or diminishing the difference between summer and winter temperature.

"Let us consider the former case first. The total quantity of heat received from the sun during one revolution is inversely proportional to the minor axis.

"The difference of the minor axis of the orbit when at its maximum and its minimum state of eccentricity is as 997 to 1,000. This small amount of difference cannot therefore sensibly affect the climate. Hence we must seek for our cause in the second case under consideration.

"There is of course as yet some little uncertainty in regard to the exact mean distance of the sun. I shall, however, in the present volume assume it to be 91,400,000 miles. When the eccentricity is at its superior limit, the distance of the sun from the earth, when the latter is in the aphelion of its orbit, is no less than 98,506,350 miles; and when in the perihelion it is only 84,293,650 miles. The earth is therefore 14,212,700 miles further from the sun in the former position than in the latter. The direct heat of the sun being inversely as the square of the distance, it follows that the amount of heat received by the earth when in these two positions will be as 19 to 26. Taking the present eccentricity to be .0168, the earth's distance during winter, when nearest to the sun, is 89,864,480 miles. Suppose now that, according to the precession of the equinoxes, winter in our Northern Hemisphere should happen when the earth is in the aphelion of its orbit, at the time when the orbit is at its greatest eccentricity; the earth would then be 8,641,870 miles further from the sun in winter than at present. The direct heat of the sun would, therefore, be one fifth less during that season than at present; and in summer one fifth greater. This enormous difference would affect the climate to a very great extent. But if winter under these circumstances should happen when the earth is in the perihelion of its orbit, the earth would then be 14,212,700 miles nearer the sun in winter than in summer. In this case the difference between winter and

* *Connaissance des Temps* for 1863 (Additions). Lagrange's determination makes the superior limit 0.07641 (Memoirs of the Berlin Academy for 1782, p. 273). Recently the laborious task of reinvestigating the whole subject of the secular variations of the elements of the planetary orbits was undertaken by Mr. Stockwell, of the United States. He has taken into account the disturbing influence of the planet Neptune, the existence of which was not known when Leverrier's computations were made; and he finds that the eccentricity of the earth's orbit will always be included within the limits of 0 and 0.0693888. Mr. Stockwell's elaborate Memoir, extending over no fewer than two hundred pages, will be found in the eighteenth volume of the "Smithsonian Contributions to Knowledge."

summer in the latitude of this country would be almost annihilated. But as the winter in the one hemisphere corresponds with the summer in the other, it follows that while the one hemisphere would be enduring the greatest extremes of summer heat and winter cold, the other would be enjoying a perpetual summer.

"It is quite true that whatever may be the eccentricity of the earth's orbit, the two hemispheres must receive equal quantities of heat per annum; for proximity to the sun is exactly compensated by the effect of swifter motion, — the total amount of heat received from the sun between the two equinoxes is the same in both halves of the year, whatever the eccentricity of the earth's orbit may be. For example, whatever extra heat the Southern Hemisphere may at present receive from the sun during its summer months, owing to greater proximity to the sun, is exactly compensated by a corresponding loss arising from the shortness of the season; and, on the other hand, whatever deficiency of heat we in the Northern Hemisphere may at present have during our summer half-year in consequence of the earth's distance from the sun, is also exactly compensated by a corresponding length of season.

"It has been shown in the introductory chapter that a simple change in the sun's distance would not alone produce a glacial epoch, and that those physicists who confined their attention to purely astronomical effects were perfectly correct in affirming that no increase of eccentricity of the earth's orbit could account for that epoch. But the important fact was overlooked that although the glacial epoch could not result directly from an increase of eccentricity, it might nevertheless do so indirectly. The glacial epoch, as I hope to show, was not due directly to an increase in the eccentricity of the earth's orbit, but to a number of physical agents that were brought into operation as a result of an increase.

"I shall now proceed to give an outline of what these physical agents were, how they were brought into operation, and the way in which they led to the glacial epoch.

"When the eccentricity is about its superior limit, the combined effect of all those causes to which I allude is to lower to a very great extent the temperature of the hemisphere whose winters occur in aphelion, and to raise to nearly as great an extent the temperature of the opposite hemisphere, where winter of course occurs in perihelion.

"With the eccentricity at its superior limit and the winter occurring in the aphelion, the earth would be 8,641,870 miles further from the sun during that season than at present. The reduction in the amount of heat received from the sun owing to his increased distance would, upon the principle we have stated in Chapter II., lower the midwinter temperature to an enormous extent. In temperate regions the greater portion of the moisture of the air is at present precipitated in the form of rain, and the very small portion which falls as snow disappears in the course of a few weeks at most. But in the circumstances under consideration, the mean winter temperature would be lowered so much below the freezing-point that what now falls as rain during that season would then fall as snow. This is not all; the winters would then not only be colder than now, but they would also be much longer. At present the winters are nearly eight days shorter than the summers; but with the eccentricity at its superior limit and the winter solstice in aphelion, the length of the winters would exceed that of the summers by no fewer than thirty-six days. The lowering of the temperature and the lengthening of the winter would both tend to the same effect, viz. to increase the amount of snow accumulated during the winter; for, other things being equal,

the larger the snow-accumulating period the greater the accumulation. I may remark, however, that the absolute quantity of heat received during winter is not affected by the decrease in the sun's heat,* for the additional length of the season compensates for this decrease. As regards the absolute amount of heat received, increase of the sun's distance and lengthening of the winter are compensatory, but not so in regard to the amount of snow accumulated.

"The consequence of this state of things would be that, at the commencement of the short summer, the ground would be covered with the winter's accumulation of snow.

"Again, the presence of so much snow would lower the summer temperature, and prevent to a great extent the melting of the snow.

"There are three separate ways whereby accumulated masses of snow and ice tend to lower the summer temperature, viz.: —

"*First.* By means of direct radiation. No matter what the intensity of the sun's rays may be, the temperature of snow and ice can never rise above 32°. Hence the presence of snow and ice tends by direct radiation to lower the temperature of all surrounding bodies to 32°.

"In Greenland, a country covered with snow and ice, the pitch has been seen to melt on the side of a ship exposed to the direct rays of the sun, while at the same time the surrounding air was far below the freezing-point; a thermometer exposed to the direct radiation of the sun has been observed to stand above 100°, while the air surrounding the instrument was actually 12° below the freezing-point.† A similar experience has been recorded by travellers on the snow fields of the Alps.‡

"These results, surprising as they no doubt appear, are what we ought to expect under the circumstances. The diathermancy of air has been well established by the researches of Professor Tyndall on radiant heat. Perfectly dry air seems to be nearly incapable of absorbing radiant heat. The entire radiation passes through it almost without any sensible absorption. Consequently the pitch on the side of the ship may be melted, or the bulb of the thermometer raised to a high temperature by the direct rays of the sun, while the surrounding air remains intensely cold. 'A joint of meat,' says Professor Tyndall, 'might be roasted before a fire, the air around the joint being cold as ice.'§ The air is cooled by *contact* with the snow-covered ground, but is not heated by the radiation from the sun.

"When the air is humid and charged with aqueous vapor, a similar cooling effect also takes place, but in a slightly different way. Air charged with aqueous vapor is a good absorber of radiant heat, but it can only absorb those rays which agree with it in *period*. It so happens that rays from snow and ice are, of all others, those which it absorbs best. The humid air will absorb the total radiation from the snow and ice, but it will allow the greater part of, if not nearly all, the sun's rays to pass unabsorbed. But during the day, when the sun is shining, the radiation from the snow and ice to the air is negative; that is, the snow and ice cool the air by

* When the eccentricity is at its superior limit, the absolute quantity of heat received by the earth during the year is, however, about one three-hundredth part greater than at present. But this does not affect the question at issue.

† Scoresby's Arctic Regions, Vol. II. p. 379. Daniell's Meteorology, Vol. II. p. 123.

‡ Tyndall, On Heat, Art. 364.

§ Ibid.

radiation. The result is, the air is cooled by radiation from the snow and ice (or rather, we should say, *to* the snow and ice) more rapidly than it is heated by the sun; and, as a consequence, in a country like Greenland, covered with an icy mantle, the temperature of the air, even during summer, seldom rises above the freezing-point. Snow is a good reflector, but as simple reflection does not change the character of the rays they would not be absorbed by the air, but would pass into stellar space.

"Were it not for the ice, the summers of North Greenland, owing to the continuance of the sun above the horizon, would be as warm as those of England; but, instead of this, the Greenland summers are colder than our winters. Cover India with an ice sheet, and its summers would be colder than those of England.

"*Second.* Another cause of the cooling effect is that the rays which fall on snow and ice are to a great extent reflected back into space.* But those that are not reflected, but absorbed, do not raise the temperature, for they disappear in the mechanical work of melting the ice. The latent heat of ice is about 142° F.; consequently in the melting of every pound of ice a quantity of heat sufficient to raise one pound of water 142° disappears, and is completely lost, so far as temperature is concerned. This quantity of heat is consumed, not in raising the temperature of the ice, but in the mechanical work of tearing the molecules separate against the forces of cohesion binding them together into the solid form. No matter what the intensity of the sun's heat may be, the surface of the ground will remain permanently at 32° so long as the snow and ice continue unmelted.

"*Third.* Snow and ice lower the temperature by chilling the air and condensing the vapor into thick fogs. The great strength of the sun's rays during summer, due to his nearness at that season, would, in the first place, tend to produce an increased amount of evaporation. But the presence of snow-clad mountains and an icy sea would chill the atmosphere and condense the vapor into thick fogs. The thick fogs and cloudy sky would effectually prevent the sun's rays from reaching the earth, and the snow, in consequence, would remain unmelted during the entire summer. In fact, we have this very condition of things exemplified in some of the islands of the Southern Ocean at the present day. Sandwich Land, which is in the same parallel of latitude as the north of Scotland, is covered with ice and snow the entire summer; and in the island of South Georgia, which is in the same parallel as the centre of England, the perpetual snow descends to the very sea-beach. The following is Captain Cook's description of this dismal place: 'We thought it very extraordinary,' he says, 'that an island between the latitudes of 54° and 55° should, in the very height of summer, be almost wholly covered with frozen snow, in some places many fathoms deep. . . . The head of the bay was terminated by ice cliffs of considerable height; pieces of which were continually breaking off, which made a noise like a cannon. Nor were the interior parts of the country less horrible. The savage rocks raised their lofty summits till lost in the clouds, and valleys were covered with seemingly perpetual snow. Not a tree nor a shrub of any size were to be seen. The only signs of vegetation were a strong-bladed grass growing in tufts, wild burnet, and a plant-like moss seen on the rocks. . . . We are inclined to think that the interior parts, on account of their elevation, never enjoy heat enough to melt the snow in such quantities as to produce a river, nor did we find even a stream of fresh water on the whole coast.' †

* See Phil. Mag., March, 1870.

† Captain Cook's Second Voyage, Vol. II. pp. 232, 235.

"Captain Sir James Ross found the perpetual snow at the sea-level at Admiralty Inlet, South Shetland, in lat. 64°; and while near this place the thermometer in the very middle of summer fell at night to 23° F.; and so rapidly was the young ice forming around the ship that he began, he says, 'to have serious apprehensions of the ship's being frozen in.'* At the comparatively low latitude of 59° S., in long. 171° E. (the corresponding latitude of our Orkney Islands), snow was falling on the longest day, and the surface of the sea at 32°.† And during the month of February (the month corresponding to August in our hemisphere) there were only three days in which they were not assailed by snow-showers.‡

"In the Straits of Magellan, in 53° S. lat., where the direct heat of the sun ought to be as great as in the centre of England, MM. Churrca and Galcano have seen snow fall in the middle of summer; and though the day was eighteen hours long, the thermometer seldom rose above 42° or 44°, and never above 51°.§

"This rigorous condition of climate chiefly results from the rays of the sun being intercepted by the dense fogs which envelop those regions during the entire summer; and the fogs again are due to the air being chilled by the presence of the snow-clad mountains and the immense masses of floating ice which come from the antarctic seas. The reduction of the sun's heat and lengthening of the winter, which would take place when the eccentricity is near to its superior limit and the winter in aphelion, would in this country produce a state of things perhaps as bad as, if not worse than, that which at present exists in South Georgia and South Shetland.

"If we turn our attention to the polar regions, we shall find that the cooling effects of snow and ice are even still more marked. The coldness of the summers in polar regions is owing almost solely to this cause. Captain Scoresby states that, in regard to the arctic regions, the general obscurity of the atmosphere arising from fogs or clouds is such that the sun is frequently invisible during several successive days. At such times, when the sun is near the northern tropic, there is scarcely any sensible quantity of light from noon till midnight.‖ 'And snow,' he says, 'is so common in the arctic regions, that it may be boldly stated that in nine days out of ten during the months of April, May, and June more or less falls.'¶

"On the north side of Hudson's Bay, for example, where the quantity of floating ice during summer is enormous, and dense fogs prevail, the mean temperature of June does not rise above the freezing-point, being actually 13.5° below the normal temperature; while in some parts of Asia under the same latitude, where there is comparatively little ice, the mean temperature of June is as high as 60°.

"The mean temperature of Van Rensselaer Harbor, in lat. 78° 37′ N., long. 70° 53′ W., was accurately determined from hourly observations made day and night over a period of two years by Dr. Kane. It was found to be as follows:—

	°
Winter	−28.59
Spring	−10.59
Summer	+33.38
Autumn	− 4.03

* Antarctic Regions, Vol. II. pp. 345–349.

† Ibid., Vol. I. p. 167.

‡ Ibid., Vol. II. p. 362.

§ Edinburgh Philosophical Journal, Vol. IV. p. 266.

‖ Scoresby's Arctic Regions, Vol. I. p. 378.

¶ Ibid., p. 425.

But although the quantity of heat received from the sun at that latitude ought to have been greater during the summer than in England,* yet nevertheless the temperature is only 1.38° above the freezing-point.

"The temperature of Port Bowen, lat. 73° 14′ N., was found to be as follows: —

Winter	— 25.09°
Spring	— 5.77
Summer	+ 34.40
Autumn	+ 10.58

Here the summer is only 2.4° above the freezing-point.

"The condition of things in the antarctic regions is even still worse than in the arctic. Captain Sir James Ross, when between lat. 66° S. and 77° 5′ S., during the months of January and February, 1841, found the mean temperature to be only 26.5°; and there were only two days when it rose even to the freezing-point. When near the ice-barrier on the 8th of February, 1841, a season of the year equivalent to August in England, he had the thermometer at 12° at noon; and so rapidly was the young ice forming around the ships, that it was with difficulty that he escaped being frozen in for the winter. 'Three days later,' he says, 'the thick falling snow prevented our seeing to any distance before us; the waves as they broke over the ships froze as they fell on the decks and rigging, and covered our clothes with a thick coating of ice.'† On visiting the barrier next year about the same season, he again ran the risk of being frozen in. He states that the surface of the sea presented one unbroken sheet of young ice as far as the eye could discover from the masthead.

"Lieutenant Wilkes, of the American Exploring Expedition, says that the temperature they experienced in the antarctic regions surprised him, for they seldom, if ever, had it above 30°, even at midday. Captain Nares, when in latitude 64° S., between the 13th and 25th February last (1874), found the mean temperature of the air to be 31.5°; a lower temperature than is met with in the arctic regions, in August, ten degrees nearer the pole.‡

"These extraordinarily low temperatures during summer, which we have just been detailing, were due solely to the presence of snow and ice. In South Georgia, Sandwich Land, and some other places which we have noticed, the summers ought to be about as warm as those of England; yet to such an extent is the air cooled by means of floating ice coming from the antarctic regions, and the rays of the sun enfeebled by the dense fogs which prevail, that there is actually not heat sufficient even in the very middle of summer to melt the snow lying on the sea-beach.

"We read with astonishment that a country in the latitude of England should in the very middle of summer be covered with snow down to the sea-shore, the thermometer seldom rising much above the freezing-point. But we do not consider it so surprising that the summer temperature of the polar regions should be low, for we are accustomed to regard a low temperature as the normal condition of things there. We are, however, mistaken if we suppose that the

* See Meech's memoir "On the Intensity of the Sun's Heat and Light," Smithsonian Contributions, Vol. IX.

† Antarctic Regions, Vol. I. p. 240.

‡ *Challenger* Reports, No. 2, p. 10.

influence of ice on climate is less marked at the poles than at such places as South Georgia or Sandwich Land.

"It is true that a low summer temperature is the normal state of matters in very high latitudes, but it is so only in consequence of the perpetual presence of snow and ice. When we speak of the normal temperature of a place we mean, of course, as we have already seen, the normal temperature under the present condition of things. But were the ice removed from those regions, our present Tables of normal summer temperature would be valueless. These Tables give us the normal June temperature while the ice remains, but they do not afford us the least idea as to what that temperature would be were the ice removed. The mere removal of the ice, all things else remaining the same, would raise the summer temperature enormously. The actual June temperature of Melville Island, for example, is 37°, and Port Franklin, Nova Zembla, 36.5°; but were the ice removed from the arctic regions, we should then find that the summer temperature of those places would be about as high as that of England. This will be evident from the following considerations: —

"The temperature of a place, other things being equal, is proportionate to the quantity of heat received from the sun. If Greenland receives per given surface as much heat from the sun as England, its temperature ought to be as high as that of England. Now, from May 10 till August 3, a period of eighty-five days, the quantity of heat received from the sun in consequence of his remaining above the horizon is actually greater at the north pole than at the equator.

"Column II. of the following Table, calculated by Mr. Meech,* represents the quantity of heat received from the sun on the 15th of June at every 10° of latitude. To simplify the Table, I have taken 100 as the unit quantity received at the equator on that day instead of the unit adopted by Mr. Meech: —

	I. Latitude.	II. Quantity of Heat.	III. June Temperature.
Equator	0°	100	80.0°
	10	111	81.1
	20	118	81.1
	30	123	77.3
	40	125	68.0
	50	125	58.8
	60	123	51.4
	70	127	39.2
	80	133	30.2
North Pole	90	136	27.4

"The calculations are, of course, made upon the supposition that the quantity of rays cut off in passing through the atmosphere is the same at the poles as at the equator, which, as we know, is not exactly the case. But, notwithstanding the extra loss of solar heat in high latitudes caused by the greater amount of rays that are cut off, still, if the temperature of the arctic

* See Smithsonian Contributions, Vol. IX.

summers were at all proportionate to the quantity of heat received from the sun, it ought to be very much higher than it actually is. Column III. represents the actual mean June temperature, according to Prof. Dove, at the corresponding latitudes. A comparison of these two columns will show the very great deficiency of temperature in high latitudes during summer. At the equator, for example, the quantity of heat received is represented by 100 and the temperature 80°; while at the pole the temperature is only 27.4°, although the amount of heat received is 136. This low temperature during summer, from what has been already shown, is due chiefly to the presence of snow and ice. If by some means or other we could remove the snow and ice from the arctic regions, they would then enjoy a temperate, if not a hot, summer. In Greenland, as we have already seen, snow falls even in the very middle of summer, more or less, nine days out of ten; but remove the snow from the Northern Hemisphere, and a snow-shower in Greenland during summer would be as great a rarity as it would be on the plains of India.

"Other things being equal, the quantity of solar heat received in Greenland during summer is considerably greater than in England. Consequently, were it not for snow and ice, it would enjoy as warm a climate during summer as that of England. Conversely, let the polar snow and ice extend to the latitude of England, and the summers of that country would be as cold as those of Greenland. Our summers would then be as cold as our winters are at present, and snow in the very middle of summer would perhaps be as common as rain."

So far Mr. Croll was not far away from the paths of his predecessors; he does not stop here, but turns his reader's attention at once to certain effects arising from the geography of the earth's surface, and the distribution of the trade-winds as affecting the oceanic circulation. In a condensed way we will follow his train of reasoning.

It is a well-known fact that the conveyance of heat from the equatorial regions to the circumpolar areas is accomplished by means of the trade-wind system of air currents and the ocean currents. The influence of the ocean currents, which Mr. Croll has finally shown to be secondary effects of the trade-winds, is far greater than that of the winds themselves. He concludes that but for the compensation that these agents bring about, the temperature of the Arctic region would be 83° colder and the equatorial region 55° warmer than at present.*

The mechanism of the trade-winds is very simple, but so often misconceived that it is worth while to restate it here. The heat of the equatorial regions causes the air to rise from the surface of the earth, and to supply its place there is a movement of air along the surface from the regions nearer the poles. For a certain distance this movement is so clear that the name of trade-wind was given to it on account of the certainty with which the sailor could reckon upon it in his

* Croll, Climate and Time in Geology, p. 42.

voyages, but towards the poles it becomes confused with other currents, so that it is not distinctly traceable. The heated air moves away from the equator in the higher regions towards the circumpolar districts, and thus a continuous current is kept up from the tropical to either circumpolar region. In volume and aggregate force these winds probably exceed all the other winds of the earth put together. If the earth were without any motion on its axis, these winds would move up and down on the line of the meridians, that is, they would come upon the equator at right angles to its line; but as it is rotating on its axis, it is not possible for any stream to flow to or from the pole without great deflections. Starting from the higher latitudes, the particle of air under the influence of the trade-winds is constantly passing to regions having a more and more rapid rate of motion, and its inertia tends to make it drop behind the rotation of the earth, or to fall off to the west. As this affects every particle on its way to the equatorial regions, the result is that the current inclines to the west. On the north, the wind is northeast; on the south, southeast; so the two currents meet on the equatorial belt at nearly right angles to each other.* As these winds move with a considerable speed, they push along the water before them, making currents of the sea that set down towards the equator, where they impinge on each other as the trade-winds do. But the air borne on the winds rises into the upper region of the atmosphere, while the water, moving at the rate of several miles an hour, opposed by a similar current from the other hemisphere, is forced to turn directly to the west, and flow on until it breaks against some shore that turns it back towards the poles. Meeting such a shore, this water from the two hemispheres, coursing along under the equator, divides again into two streams, which flow on until the momentum given them by the trade-winds is slowly exhausted by the friction of the sea through which they flow, or by opposing winds. When they turn towards either pole, they take with them the rate of rotation of the earth at the equator, and, constantly proceeding to regions having a less rapid movement of rotation, they move off to the east in the direction of the earth's motion on its axis.† Now it is to these currents of the sea, of which there are five in number, the Gulf Stream being the most

* If the reader needs to get a vivid idea of the action of inertia, it will only be necessary to take any revolving disk, such as a potter's wheel, and while it is rotating slowly, roll a small ball from the centre towards the periphery. He will see that the ball cannot go in a straight line, but meets the periphery of the wheel, which answers to the equator of the earth, in an oblique direction.

† By pushing the shot from the periphery of the wheel towards the centre, which represents the pole of the earth, this will be well shown.

conspicuous and on the whole the most powerful, that we owe the principal part of the carriage of heat from the tropics towards the poles; for, as Mr. Croll shows, the Gulf Stream alone is probably more effective in this work of conveying heat than all the air currents put together. So anything that would tend greatly to change the work of these streams would have the most momentous effects upon climate. Mr. Croll has ingeniously suggested that the following effects would follow from the creation of a glacial sheet over the whole circumpolar tract of a hemisphere, while the opposite pole was enjoying a period of almost uniform and rather high temperature. The vigor of the trade-wind in either hemisphere is determined by the difference between the temperature of that pole and of the equator. The first effect, therefore, of having one polar region much warmer than the other would be to increase the intensity of the trade-winds in the glaciated hemisphere, while those of the other hemisphere would be diminished in force. Now it happens that the Gulf Stream is divided by the eastern promontory of South America, known as Cape St. Roque, which projects as a great shoulder into the sea; all the water of the equatorial stream that strikes the northern side of this cape passes into the North Atlantic, that which is turned to the south seeks a way toward the South Pole. It is clear that if the northern trade-winds were even a little stronger than at present, the equatorial current would have its central part driven farther south, and Cape St. Roque would set off a larger share of its waters to the southern seas, while any very great excess of power of the northern trade-winds would, perhaps, drive the whole of the equatorial current so far south that it all would strike on the southern slope of this cape. Now Mr. Croll's idea is, that the conditions of cold climate in the northern regions would intensify the trade-winds of that hemisphere, and, there being at the same time a warm climate about the Southern Pole to weaken the trade-winds of that hemisphere, we should have the centre of the equatorial current pushed, perhaps, altogether south of the point of the cape, and the Northern Atlantic robbed of the whole of the heat which that great river of the sea now brings to it: when the Southern Hemisphere was under ice and the Northern in its state of equable climate, the reverse condition would arise, the Southern Hemisphere being in large part deprived of the heat that now falls to it.

There can be no doubt that this is a most important suggestion, yet we find difficulties in giving too much value to it. In the first place, the lower the temperature of the Northern Hemisphere during the period of glaciation, the more con-

siderable are our difficulties in accounting for the great amount of rain-fall which is necessary to supply glaciation of such prodigious extent. If we take the Gulf Stream from the North Atlantic, we should so lower its temperature that relatively little evaporation would take place there. Then all or nearly all the water supply to feed the glaciers would have to come from the equator in the water borne by the counter trade-winds. These winds are not powerful conveyors of water; there is very little reason to believe that they contribute much to the transportation of water from the equator to the high latitudes at the present time, and, entering as cold a hemisphere as the North Atlantic would be without the Gulf Stream, it hardly seems possible that they could supply a circumpolar ice sheet in an effective manner. Moreover, while it is possible that Cape St. Roque bore something like its present relation to the equatorial current during the last ice time, it cannot be supposed that during preceding glacial periods it was there to do its work. The fact that in the lands in about the same latitude there are evidences of recent submergence to the amount of over sixteen hundred feet shows that the assumption that Cape St. Roque had its present geographical outline even during the last glacial period is not perfectly safe, especially when we consider how little is known concerning the geology of that district. Although this hypothesis is not absolutely necessary to Croll's general theory, its acceptance would, in his opinion, aid in the explanation of the glacial conditions.

To return to the general aspects of Mr. Croll's theory, it should be noted that the glaciation brought about in the manner described would continue for about eleven thousand years in one hemisphere, and would then, on account of the precession of the equinoxes, be transferred to the opposite pole, the region abandoned by the ice becoming the seat of a climate the opposite of that which it had just escaped from; and so the glacial conditions would swing from pole to pole until the eccentricity of the earth's orbit had been reduced to something like its present condition. As it requires only about twenty-five thousand years to swing the equinoctial points through their whole revolution about the orbit, an ordinary period of extreme eccentricity would give a chance for a succession of half a dozen or more of these alternations in either hemisphere.

We have now given a brief review of the opinions of this able writer: the reader should be tempted, by the originality and power of these hypotheses, to pursue them further in the works of the author. We must next turn to another hypothesis, which has also received light from the discussions of Mr. Croll, but is not so particularly his own as that we have just set forth.

Among the early speculations that were brought forward to account for the changes of climate, of which the new studies in the earth's history had furnished so many proofs, was that of the change in the earth's axis of rotation. The common form of the theory was to the effect that some errant mass from space, generally the fateful comet, falling on the earth's surface had given it a shearing blow strong enough to change the axis far from its original place, and so bring a part of the tropical lands near to the pole. It is not to be denied that such collisions are certainly possible, but it is certain that no body as large as a mile in diameter, certainly none large enough to affect the earth's axis of rotation, has struck upon its surface since the time our organic life began. A body a mile in diameter falling from the celestial spaces with the speed of our meteors — and it could not well fall at a less rate — would apply force which would at once be converted into heat sufficient to produce a destructive revolution in the life of the earth. A single blow upon the earth powerful enough to produce any important effect upon the position of its axis of rotation would probably reduce its crust to a molten state. There are, however, one or two causes of gradual change in this axis that are the source of more or less certain variation in the inclination of the earth's axis to the ecliptic, or in the actual position of this axis. To take the more questionable first, it has been suggested that in case the earth consisted of a hard outer shell resting upon a fluid interior, the attraction of the moon upon any very great protuberances in the shape of extensive mountains or continents elevated in the high latitudes, might, if there were no counterbalancing elevations in the other hemisphere, lead to a sliding of the outer crust on the fluid interior; but it now seems pretty certain that the interior of the earth is not, in any proper sense, fluid, — that is, that it has so much rigidity that it would not slide in the manner suggested, — so this hypothesis has been generally abandoned. Very recently it has been suggested that this attraction on the masses elevated in either hemisphere might operate, even if the earth were solid, to force the whole mass out of its original axis of rotation. The most careful mathematical discussion seems to indicate that there is a possibility of some small change coming in this fashion, but that the change, even under the most favorable circumstances, could not exceed a very few degrees of latitude, and is hardly worth consideration. The most valuable suggestion that can be made concerning the relation of the earth's rotation axis to the equator is that which has been much discussed concerning the change in the obliquity of the ecliptic. The ecliptic, as the reader doubtless knows, is the great circle marked out by the sun in its apparent annual path among the fixed stars;

its plane contains the path along which the earth travels in its orbit. This plane is not always in the same position in reference to the earth's axis of rotation that it is now. The change is of somewhat doubtful amount, but the best authorities agree that it does not at the most exceed 2° 37′ 22″. Lieutenant-Colonel Drayson has written a singular book to show that the variation in this obliquity may amount to as much as 12° in sixteen thousand years, but his computations have not yet received the approval of other astronomers.* Assuming that the angle of the ecliptic varies no more than it is commonly supposed to, the effect of the change, though considerable, would not be revolutionary. It would be equivalent to pushing the Arctic Circle, or the line where the sun remains above the horizon for more than twenty-four hours, to and fro, now nearer the pole, now nearer the equator, by the amount of the variation. After an elaborate and sound consideration of the question, Mr. Croll concludes that the total change possible would result in increase in the amount of heat received by the Arctic Circles to the amount of about 8.45 thermal days each year, or one eighteenth the amount of heat now received in those circles from the sun, and that the direct and indirect consequence of this change would be to increase the average heat within these circles by about 15° Fahrenheit. It must not be supposed, however, that all this heat would go to raise the temperature of the polar regions. This would be the case during the times when the Arctic Circles were in succession clear of ice; but when they were ice-bound, this additional heat would be, in the main, applied to melting the ice and snow that occurs there, without making any material addition to their general temperature. In their glaciated condition the result would be merely a considerable reduction in the depth and area of their ice deposits. Coming in a time of glaciation, this change would doubtless tend to give a momentary set-back to the advance of the ice, while at other times it would help to lift the general temperature, and make those regions more habitable than they would otherwise be. Before Mr. Croll took up this subject, several writers had seriously misapprehended the nature of the effects due to the variation of the obliquity. Because the Arctic Circle was brought farther south in the periods of extreme obliquity, they have concluded that the region

* My friend Professor Newcomb, to whom I turned for a critical opinion on Colonel Drayson's theory, assures me that he considers it entirely devoid of foundation. He says: "The mathematical theory of the motion of equator and ecliptic is thoroughly founded, and no observations have yet shown any deviation from it. Drayson's results were obtained by selecting a few old obliquities which of course were erroneous, some modern observations, and some calculated positions given by the very theory which he was trying to demolish, and combining the results without regard to gravitation or any other law."

included within them would be made colder by the change. Mr. Croll has conclusively shown that the reverse would be the case, and that an increase of obliquity would tend to warmer, not to colder conditions. The general effect of the increase of the obliquity is to diminish the amount of heat received in the equatorial belt, and to apply the heat nearer the polar regions. On this account we may follow Mr. Croll in dismissing Colonel Drayson's theory, for, however interesting it may be from the point of view of astronomy, it apparently cannot alone account for the phenomena of glaciation.

There remains yet another suggestion concerning the cause of the glacial periods that has been made by several writers. As soon as it became evident that we must look to regions beyond the earth for the conditions that brought about glaciation, naturalists properly turned to the hypothesis that they might be due to the changes in the heat of the sun itself. So far these conjectures have been confined to supposing that glacial periods were due to the falling off of the sun's heat and the consequent refrigeration of the earth. There is no question that we are justified in considering the sun as possibly a variable star. Of the few thousand stars that are easily visible to the naked eye, many are subject to periodic variations of sufficiently brief intervals to make them noticeable to astronomers. Other stars, though so far but few, have been observed suddenly to flame up in a way that shows that from some cause they have increased their light and heat many fold. Undoubtedly the space of a million of years would bring about such changes in a large part of the suns in the visible universe. A change in the light and heat of our sun sufficient to alter its apparent size by half a magnitude would mean an utter revolution in the conditions of our earth, either reducing it to cold that would extinguish life or filling the air with the water of the seas. But the hypothesis that the glacial period could be produced by a loss of heat of the sun will not stand a moment's examination. What we need to account for such periods is a large amount of rain-fall. We see now great areas, such as British America and Siberia, that are cold enough for glaciation, but want the snow-fall and other conditions of humidity that would make glaciation possible; none of these conditions would be brought about by a general refrigeration of the earth. The only form in which an alteration in the solar temperature could effect the required change is by the increase in the heat from the sun. If the solar heat should be increased so as to add one half to the rain-fall of the earth, the result would probably be a great increase in the equatorial temperature, and a considerable increase of rain-fall over the whole

earth's surface. The polar regions would be the recipients of their share of the water; their ice areas would extend to wide tracts where the lack of sufficient rain-fall is all that keeps them from being covered by ice. A certain gain of temperature would doubtless come to the circumpolar regions from the rise in the general temperature of the earth, but this might be considerable without involving any change in the conditions that favor the extension of the ice. Moreover, all the increase of the temperature of regions within the Arctic Circle would at once increase the cloud wrap that now to such an extent shelters their ice from the action of the sun. Mr. Croll has very effectively discussed the action of this cloud envelope during the summers of the time when eccentricity produces glaciation on either pole. The same considerations would apply with equal force to the conditions of the poles during times when the earth's heat was somewhat greater than at present. Of course any increase in the sun's heat, such as would bring the average temperature of the poles up to that which now prevails in latitude 40°, would dissipate the glaciers there; but inasmuch as the long winter night in such conditions would necessarily have a low temperature and a great snow-fall, the summer season would have difficulty in removing all the snow that fell. It is not necessary now to consider this suggestion in detail, but it seems a most likely cause of glacial conditions.

Yet another cause of glaciation has been suggested by several authors; it depends upon slight changes of geography, such as are quite within the limits of ordinary changes dependent on geological disturbances. The course of the Gulf Streams, if by this name we may designate the branches of the equatorial trade-wind current that make their way towards the poles, depend for their origin and direction of flow upon the accidents in the position of the shore lines. Slight changes of geography, as we may see by what has been said concerning Cape St. Roque, may cause the deflection or destruction of these currents, bringing momentous changes to either pole. If Cape St. Roque had, in its building, been put two hundred miles farther north, all Northern Europe would have been uninhabitably cold, colder by far than the shores of Hudson's Bay. Yet there are many accidents of this class, that from time to time serve to turn these streams away. A lowering of the Isthmus of Panama — which must have happened more than once in recent geological times, as is shown by its geology, and by the character of its marine animals on either side of its barrier — would turn a part of the Gulf Stream into the Pacific, and lower the temperature of Europe. The Asiatic Gulf Stream, the Kuro Siwo, that

makes its way along the coast of Asia toward the Arctic Circle, is barred from the polar waters by the peninsulas of Asia and America, that, drawing together, leave but a narrow passage in Behring's Strait. The depression of these lands, which probably existed when they escaped from the ice of the last glacial period, would have left a way open for the penetration of this current into the Arctic Sea. This would have lifted the temperature of the Arctic Circle by many degrees, and proportionately lowered that of the tropical regions. Such changes as these are necessarily of constant occurrence in geological revolutions, and many of the great alterations of climate in the past are doubtless to be attributed to them. The accident of position of these lands that bar the Japan current from the Arctic Seas must be subject to constant change by the elevation and depression of the continents to which they belong. There is little doubt that the comparatively recent elevation of the Sahara above the level of the sea brought about considerable changes in the oceanic circulation; and in the discussion of the climatal conditions of Europe, it has indeed been attempted to explain the former great extension of the Swiss glaciers by the fact that during their period of maximum extension this region was probably still a sea, giving moist winds to feed the glaciers in place of the sirocco that melts them with its hot dry air. Many instances such as these could be brought forward to show the evident power of geographical change, and its competency to effect the extension of glaciers in either hemisphere. But it is clear, as before remarked, that no conceivable array of the geographical features of our earth can explain the occurrence of such a glacial period as that from which the earth has emerged. For that we require agents of more general power than we can believe the variations in the position of land and sea can afford.

We have now passed in brief review the various important hypotheses that have been advanced to account for the occurrence of glacial periods; it will fall to us to choose from them the forces which we will accept as affording the most rational explanation of glaciation. But before we proceed to this part of the subject we shall find it advantageous to glance at the records of former glacial periods, with a view to ascertaining how far their times of occurrence, or the extent of the region they affected, throws light on the general aspects of glacial phenomena.

CHAPTER VII.

ANCIENT GLACIAL PERIODS.

Transitory Nature of Glacial Record. — Nature of Evidence of Glaciation. — Tertiary Glacial Periods. — Ice Action in Cretaceous Time. — Jurassic Period. — Triassic Period. — Extensive Glaciation in Permian Period. — Carboniferous Glacial Period. — Ice Action in Cambrian Period.

AS soon as the magnitude and importance of the last glacial period became clear to geologists, they at once began to consider what evidence we have of ice action in earlier stages of the earth's history. At first the results of this inquiry did not seem to be very promising; but if we keep in mind the difficulty there is in preserving any record of a glacial period in the form in which it was written, or in a shape to be readily intelligible, it will not be a matter for surprise that our opportunities for information on this point are as imperfect as we find them.

All the other great geological agents write themselves in a permanent fashion on the earth's surface. The seas make their record in the vast deposits they accumulate; volcanoes leave evidence of their action in the dikes and lavas they eject; but glaciers make a record that is from its nature transitory. A few beds of pebbles, a surface scratched and worn, is all that remains to show the work of the sheet of ice that lay over the northern half of our continent during the last period of ice. Already more than half of this waste has been worn off by the waves of the receding sea, or by the streams that have wandered to and fro in their uncertain courses. Even the deeply grooved rocks must pass again beneath the hammer of the surf as they sink down to be covered by succeeding deposits, and so be worn out of all semblance to their present form.

The power of terrestrial and sea-shore erosion is well shown by the destruction

of volcanic cones. We know that such cones have existed in every geological period since the earth's history began, by the lavas and other remains of their activity, yet not a single cone of remote geological periods is known to us in a recognizable form. Despite the fact that volcanic cones are much more resisting to erosion than glacial deposits, yet the process of wear is so effective that soon after the volcanic forces die out beneath any mountain, it is worn down to its roots, and nothing is left upon the surface except its greater lava flows, and sometimes the ash-beds that have accumulated around it.

We must be prepared, therefore, to accept other evidences of glacial action than those we find for the last glacial period, when we seek to trace the old ice times of the earth's history. The principal evidences we can hope to find are as follows: —

1st. We may find the mass of the glacial remains, boulders, gravel and sand, strewn about by the sea in the fashion in which the detritus of the last ice epoch has been and is still being strewn over the floor of the seas along our northern shores.

2d. In the deeper sea deposits of any glacial period the icebergs of the time may have here and there deposited some masses borne from the remote lands.

3d. The generally lifeless character of the deposits of glacial origin will show the effects of the cold waters in which they were formed; or, if there are fossils, they will perhaps, by their character, prove the low temperature brought about by the neighborhood of ice.

Going back to the past, we shall expect to find at each step less and less evident proofs of glaciation, for the reason that glacial deposits, even in the secondary form in which they appear after having been handled over by the sea, are always accumulated near the coast lines, and it is such shallow water deposits that are most apt to be destroyed in that constant uplifting and down-sinking of the shores.

With these facts in view we shall find, in the pages of the earth's great stone book, abundant evidence that glaciers have been actively at work at many stages in the earth's history. The first stage back of the last glacial period at which we find evidence of glaciation is the Miocene period. The best evidence of extreme ice action at this time is afforded by the sections in the hill of the Superga near Turin, which have been well described by Gastaldi, and afterwards by Lyell. In this hill, which is composed of deposits of Miocene age, quarries have been opened to get access to great quantities of granite boulders, which by their composition

have been proved to have come from the southern slope of the Alps, over a distance of from twenty to eighty miles. Here boulders are scratched in the same fashion as the boulders on the Swiss moraines. There can be no doubt that at this time in this place glaciers extended down to the Miocene sea. As this point could not have been glaciated in this fashion unless the ice had been as extensive as it was during the last glacial period, we are justified, from it alone, in inferring that the continent of Europe underwent a very extensive glaciation in the Miocene time. Mr. Croll thinks that this ice period may have been "even more excessive than the intensest severity of the climate of the last glacial epoch."

In this same geological period, though perhaps separated from the time of the Superga glacier by many tens of thousands of years, we had a period when plants of a general character comparable to those found in forests of regions as much as twenty degrees south of that land flourished in a luxuriant way. Such are the alternations that seem to attend glaciation, and which are, we must confess, better explained by Mr. Croll's hypothesis than by any other.

One step farther back in geological history brings us to the Eocene period, the earliest of the Tertiary deposits. Here we have another series of evidences showing the existence of great glaciers in the Alps,—evidences far more extensive, if not as convincing in their nature as those of the Superga locality. In Eastern Switzerland we have a very thick series of deposits of Eocene age, known as the Flysch, principally composed of coarse conglomerates containing enormous boulders not derived from the Alps, which at this age were probably of much less height than they have now. It seems most likely that this waste was derived from the worn-down mountains of the Vosges or Black Forest, which then were probably the highest mountains in this central part of Europe.* Many of these boulders are of singularly great mass; one of them, on the shores of the Lake of Thun, is one hundred and five feet long and forty-five thick.

It is a remarkable circumstance that the deposits presumably of the same age as the Flysch in other regions have not as yet afforded us any evidence of glacial action. But this may be explained by the fact that the tertiary beds are generally of a rather soft and incoherent nature, and are readily worn away by the action of ice. They are rather rarely found in those parts of Europe where the

* It is not impossible that these boulders have had their physical constitution somewhat changed by the metamorphic agents that have worked upon them, or perhaps the rocks whence they came have had their constitution altered. It needs some such supposition to account for the difficulty that geologists have found in ascertaining the origin of this enormous mass of débris.

last glacial period acted with its greatest vigor, and in North America we can almost mark the line of the ice by the limit of the destruction of the Tertiary beds. Except in shreds and patches this part of the geological record has been effaced within the glacial belt by the erosive power of the more recent ice times. This same consideration, though in a lesser degree, applies also to the more ancient glacial records of which we are still to trace the history.

One step farther back in the geological series brings us to the rocks of the Cretaceous age. In Europe the Cretaceous deposits are generally of deep-sea origin. The whole of the chalk is of this nature, and so are most of the other deposits of this age in the region that is now the Alps. We have a tolerably continuous record of the geological successions of that time, and in them nothing that clearly suggests the existence of glaciation, though a few boulders have been found there. It is reasonable to suppose that glaciation did not considerably affect this stage of our earth's history, yet in England boulders have been frequently found in the chalk that must have been carried there by floating ice in the shape of icebergs. We may safely conclude that glacial ice existed somewhere in the region to the north of these scattered boulders. It is interesting to note that here, as during the Eocene and Miocene times, the general character of the fossils indicates a generally warm climate; that is, the ice does not seem to be attendant on any general refrigeration of the regions where it occurs.

The next formation to be searched is the Jurassic. In this series of rocks there have as yet been few evidences found to show the existence of glacial periods, but in Northern Scotland there are coarse conglomerates, probably of Jurassic age, having an appearance that has led Mr. James Geikie to conclude that they are of glacial origin.* In the valley of the Connecticut and southwards along the Appalachians we have an extensive series of sandstones and conglomerates, in a part of which lie the footprint beds so well known to geologists. These beds are either of Triassic or Jurassic age. The great thickness of these conglomerates, the generally lifeless character of the sandstones associated with them, as well as the subangular forms of many of the pebbles, make it probable that what we have here is a deposit of rearranged glacial drift, such as is forming to-day at the estuary of this same river, by the reworking of the glacial drift that has just come into possession of the sea. The pebbles have exactly the same composition as those found in the modern drift, and in aspect are essentially indistinguishable

* Philosophical Magazine, Vol. XXIX. p. 290.

from it when rearranged by the sea. There seems every reason to believe that this mass is of glacial origin.

In the next great section of the earth's crust, the Permian period, we have an almost world-wide extension of glacial waste. The first indubitable evidence of glacial periods in the remote past was found in deposits of this age by Professor Ramsey, now the Director of the Geological Survey of Great Britain. These beds are in the central parts of England in the Malvern and Abberly Hills, in South Staffordshire and elsewhere. It seems pretty certain that the boulders in this district, many of which have been brought from thirty miles or more away, are of glacial origin. That distinct scratches are not found upon them is not against this view, for the scratches are often wanting in the pebbles and boulders of the last glacial period. Indeed, the proportion of pebbles that in any glacial deposit are distinctly scored by the ice is usually very small. The large size of these boulders, some of them being two feet in diameter, their subangular forms, the distance from which they have been transported, all point inevitably to the conclusion that they are of glacial origin. Many other parts of Great Britain exhibit glacial deposits of this Permian age. In Scotland, in the island of Arran, in Ireland at Armagh, we have equally conclusive evidence of ice action.

Even in the Southern Hemisphere we have what seems to be conclusive proof that the glaciers during this age operated in regions nearer the equator than they did during the last glacial period. In South Africa, in the province of Natal, a widespread area of Permian rocks is filled with boulders. Dr. Sutherland is of the opinion that these boulders, many of which weigh as much as from five to ten tons, have been transported to the parts where they lie by glaciers. Professor Ramsey thinks that many of these boulders have been carried to the distance of from sixty to eighty miles from their point of origin. In close relation to these boulder beds, we have deposits containing shells, corals, etc., of genera that now only inhabit very warm waters. In short, the evidence which we may gather from the distribution of the boulder beds of the Permian age warrants us in the conclusion that at this time in the earth's history we had a far more intense glacial period than that which has just passed away from the earth. Moreover, the evidence points to the simultaneous occurrence of glaciation about either pole. At the same time we see, by the deposits in South Africa and within the Arctic Circle, that the period was attended by times of great warmth, when the subtropical life ranged near the poles.

There are yet other evidences of high temperature in this Permian period, and in the early part of the Trias, which immediately succeeded it. In the lower part of the deposits of the last-named period, we have, in many regions, some extending as far north as Central and Northern Germany, which contain thick beds of salt, etc., that could only have been made during times of peculiarly intense evaporation, when the waters of shallow, landlocked seas were taken away in the state of vapor, leaving their salt in strata that were buried beneath subsequent deposits. So we may fairly assume that this glacial period was not one of great cold, and that it was followed by a time when the earth was subjected to intense and wide-spread desiccation, such as could only have been brought about by a high and continuous heat.

The Carboniferous deposits are but the continuation downward of the Permian system of rocks. In them we find throughout the same and even more extended evidences of ice action. With rare exceptions, wherever we see a full section of coal-bearing beds, we find them resting upon a deep deposit of boulders. No other deposit of conglomerate has anything like the wide extent that belongs to this Millstone Grit epoch of the coal period; we find it from Southern France to Scotland, from Alabama to New Brunswick, in India and elsewhere. Everywhere within the limits of recent glaciation these conglomerates have the same general character. In the Appalachian district of North America they are composed of the rocks which have been brought from the northward, until we get south of the line of the last glacial period. South of Pennsylvania they are composed of materials brought from the old range of the Blue Ridge in Virginia, North and South Carolina. In Nova Scotia these conglomerates are not clearly defined, in Pennsylvania they are about one thousand feet, in Eastern Kentucky and East Tennessee their thickness rises to about two thousand feet, and in Tennessee they are even thicker. It is evident that when we get south of the Potomac, the region acted on by the ice was composed of deeply decayed rocks, such as are now found in the Carolinas, for there the conglomerate pebbles are composed in the main of quartz, the only material that now survives the decay that has penetrated so deeply in the greater part of the rocks of these regions south of the line to which glaciers ordinarily extend.* In the midst of these conglomerates we have intercalated layers of coal. Indeed, at least two of the most valuable beds of coal

* For a fuller discussion of these beds see a paper in Vol. II., Memoirs of the Kentucky Geological Survey, now in press.

in Kentucky lie beneath the main mass of the Millstone Grit. Even after we rise above the deep deposits of pebbles and are fairly within the coal measures, we have occasional returns of conglomerates, and are constantly in the presence of grits and coarse sandstones that show that a powerful erosion was going on upon the surface of the main-lands. It is specially to be noticed that the occurrence of coals in connection with these conglomerates is proof that this great ice period, for such we must deem it, was not a time of general cold. Mr. Croll has urged that each of the several coal-beds of this series of rocks may answer to one of the interglacial periods required in his theory. The difficulty in accepting this explanation would be that in some of our carboniferous districts we have not less than forty coal-beds, and in these cases the sections have lost perhaps half their thickness by erosion. I have no doubt that if we could get the full history of the coal measures in Kentucky, we should find that there had been at least sixty successive stages at which coal had been deposited. Now it is almost impossible that any period of eccentricity could have lasted long enough to have given such a number of interglacial periods. The precession of the equinoxes on which they depend would require twenty-five thousand years for its completion, so that the total glacial period would have comprised not less than one million five hundred thousand years, or more than eight times that which we reckon as comprised by the last glacial period. Computations for the eccentricity of the earth back to this remote time are not yet made. But if it should happen that at any time there was a period of this length during which the earth's orbit was very eccentric, then Mr. Croll's theory would receive a very strong support; if, however, no such period should appear, we must feel very doubtful of this part of his admirable hypothesis.*

We may say of the Carboniferous period as of the Permian, though with more force and certainty, that it extended ice action over a wider meridional range than any that have succeeded it. We may also say that to its peculiar climate, whatever that climate may have been, we owe the important succession of events that has laid up for us in the beds of coal a vast store of solar force for the use of the arts on which civilization rests.

Descending below the coal measures, we have to pass through a considerable thickness of rocks before coming to any deposits which we can suspect to be the

* It should also be remarked that some of our coal seams have been observed to divide into several distinct beds, which became separated by considerable thickness of strata, and also that adjacent basins, or even neighboring parts of the same basin, vary very much in the number of seams they exhibit. These facts are much against Mr. Croll's suggestion that the successive coal seams answer to interglacial periods.

product of ice action. From the coal measures to the Oneida conglomerate, the earth seems to have had a period of repose in which the economy of its surface was not affected by glacial erosion. We must not, however, be too certain of this fact, for the reason that most of the strata of this age that have been studied were made in deep seas where the glacial action would be unlikely to penetrate. In the horizon of the Oneida conglomerate and the Medina sandstone we have pebbly beds which may possibly indicate ice action. As yet, however, nothing has been found that can be taken as proof that glaciers existed in this time. It is here, however, if anywhere in the Middle Palæozoic rocks, that we must look for evidences of glaciation. We must descend to the Lower Cambrian beds before we find other good evidence of glaciation.

At the base of the Cambrian rocks we have a wonderful development of conglomerates. This series of pebbly beds has been recognized at almost every point where the Cambrian series is well exposed, but its most complete development is along the flanks of the Appalachian system of mountains from the St. Lawrence to Georgia. This deposit is, at many points, of extraordinary thickness, and indicates a vigor and continuity of action on the part of the erosive forces that is probably without example in any other section of the earth's surface known to geologists. The most massive strata are found in Eastern Tennessee and Western North Carolina. Resting upon the upturned and eroded edges of the old Laurentian rocks, these conglomerates of the Ocoee period have a thickness of somewhere near twenty thousand feet. Some part of this vast depth may be due to cross bedding, but it is clear that this is the thickest single section in our American Palæozoic deposits. Above it lie ten thousand feet more of sandstones, the Chilhowee series, which mark the decadence of the forces that had their culmination during the formation of the conglomerate. Here there are thirty thousand feet of beds made from the erosion of the old Appalachian island. This deposit probably does not continue to any great distance from its old shores in anything like this thickness, yet, however limited it may be in the regions where it is hidden from sight by newer rocks, we must believe that it represents one of the greatest periods of erosion that the earth has undergone. No scratched boulders have yet been observed in this deposit; but the exposures are infrequent, and have been seen by very few geologists, so that this cannot be urged against the theory of its glacial origin. Recollecting that we know of no force that is competent to bring together such masses of pebbles derived from a wide-spread

surface save glacial action, we are justified in believing that this deposit is the product of ice action, though the waste has evidently been worked over by water since its production.

The region to the north of this district has no conglomerate so thick as those which we have just described; indeed, it seems a common fact that the ancient conglomerates are found at their thickest in the southern parts of the area affected by glaciation. The reason for this is tolerably evident: it is the southern section of the ice sheet toward which the waste all tends, and where subsequent glaciation is least likely to wear it away. Deposits of this Lower Cambrian age are found all along the line of the old Appalachian axis from Tennessee to Canada. Very good examples of it are found in the Roxbury conglomerates near Boston, Mass. These conglomerates have a thickness of somewhere near five hundred feet, and are composed of materials derived from various points in Eastern Massachusetts or Southern New Hampshire. The pebbles are rarely over a foot in diameter, yet their frequently subangular forms and the wide range of substances associated together make it pretty clear that they have a glacial origin. No distinct scratches have been observed upon them, yet the same absence of scratches is observable in the rearranged table drift, of essentially the same aspect, but deposited in the last glacial period, that at many points rests immediately upon the older conglomerates. If the overlying beds could be stripped from the flanks of the Alleghanies from Canada to Georgia, I am inclined to believe that these ancient conglomerates would be found to be nearly if not quite continuous along the whole of this line. Next after the Millstone Grit, the conglomerate at the base of the coal measures, this is the most continuous conglomerate known to me.

While there is but one great conglomerate in the Cambrian section of East Tennessee, the deposits of the same age in more northern regions show us several beds of this character at different levels in the great section of rocks that this period affords us. As yet these conglomerates have been but little studied, and we have no data for determining at just what times they were formed. It should be noted, however, that the existence of several successive conglomerates in the northern section of the Cambrian while but one was formed in the southern section entirely accords with the theory that they mark the action of ice in this period. The farther south we go, the more likely we are to get beyond the limits of the successive ice sheets.

This Cambrian conglomerate is the most ancient of which we have any trustworthy evidence.*

In the Laurentian series which underlies all our other deposits, there are many beds which may prove to have been originally conglomerates, but too little is yet known of this the greatest section of our rocks to enable us assuredly to say that glaciers existed while they were forming; yet, inasmuch as the Cambrian ice period seems to have been one of the most powerful recorded in the rocks, it is a fair presumption that they existed in earlier days.

The appended section shows, in an imperfect fashion, the formations supposed to have experienced glaciation in the succession of strata from the beginning of geological history down to the present day. The presence of glaciers, as already explained, is indicated by the occurrence of conglomerates, etc. It will be seen, from this section, that there are not less than a dozen periods where we have more or less distinct evidences of ice action. If we now consider in how few formations we have any trace of the ancient shore-lines or level surfaces in the record of the rocks, it will be seen how improbable it is that all glacial periods have left us a record. We should also bear in mind the fact that some of these ice periods are proved to us by the local occurrence of a single conglomerate, as, for instance, that of the Miocene, preserved to us by a fortunate combination of circumstances. Thus the conviction that the records are extremely imperfect becomes well assured.

* We have limited our downward search for conglomerates to the Cambrian. Below it lies a great section of rocks that have been termed, by some of our ablest geologists, the Huronian series. By others it is maintained that this series of rocks is the equivalent of the Cambrian or Cambro-Silurian, and that their peculiar aspect is due to the metamorphism that has overtaken them at particular points. If we accept the Huronian as a well-established period of the earth's history, as, in the opinion of the writer, we shall have to do, we shall then be able to say that there are earlier stages of the earth's recorded history in which glacial action possibly occurred, as is shown by the existence of some conglomerates in that series of rocks. On this basis we should come to the rather startling conclusion that the earliest times recorded in our rocks were periods of more extensive and probably more frequent glaciation than the more recent geological periods.

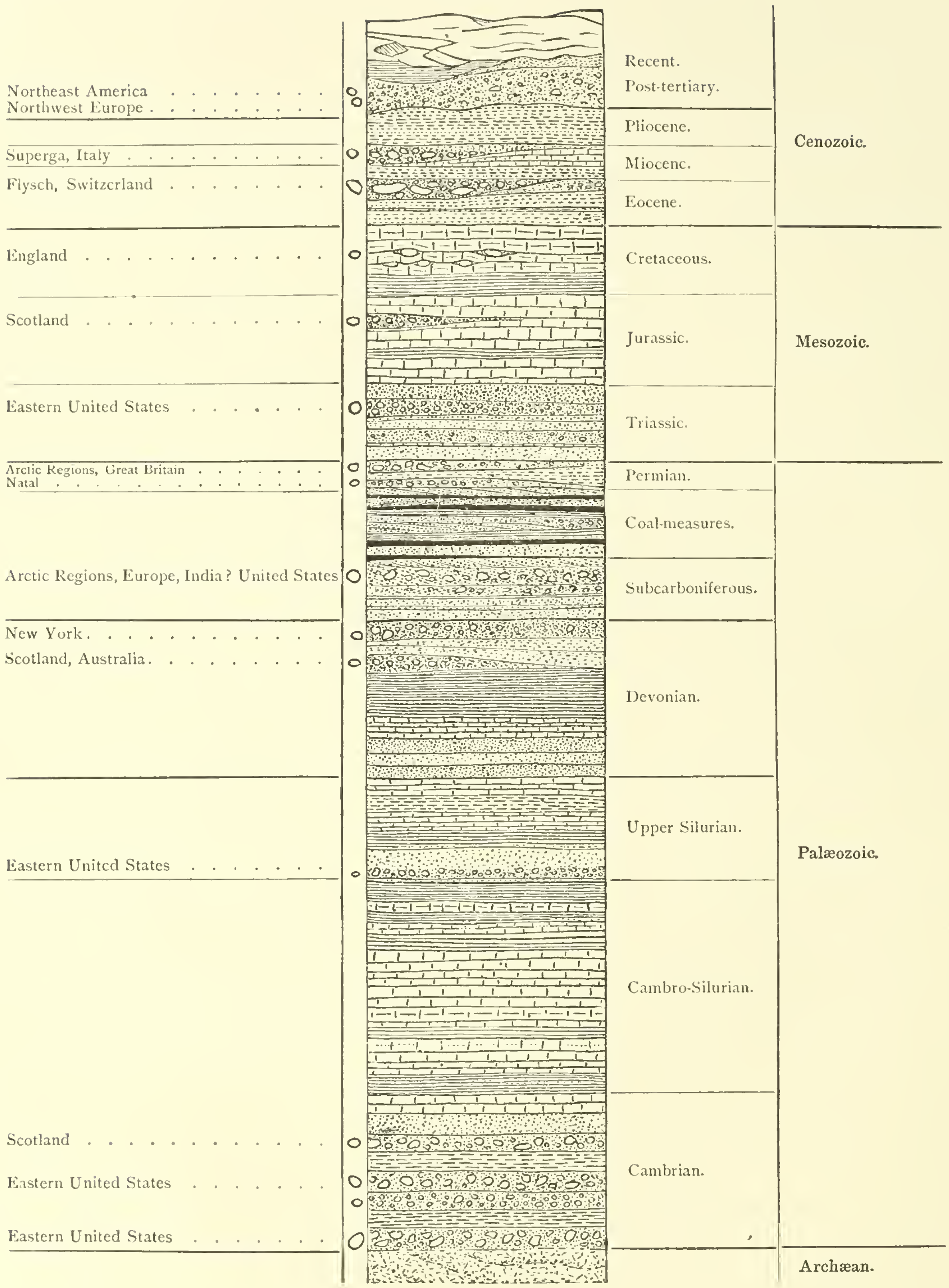


FIG. 17.

A GENERAL SECTION OF THE STRATIFIED ROCKS, SHOWING THE LOCALITY AND AGE OF THE MORE IMPORTANT CONGLOMERATES, AS INDICATING THE DATE OF POSSIBLE GLACIAL PERIODS IN THE REMOTE PAST.

The thickness of the various formations is drawn proportional to the time supposed to have been occupied in their formation

CHAPTER VIII.

THE CLIMATAL CONDITIONS OF THE GLACIAL PERIODS.

Glacial Period not a Time of Low Temperature. — Character of Life during this Period. — Heavy Rain-fall. — Fitness of several Hypotheses. — Croll's Hypothesis. — Le Coq's Hypothesis. — Lyell's Hypothesis. — A Composite Theory the most Reasonable.

BEFORE seeking to criticise the several theories concerning the cause of glaciation, we should endeavor to gather from the various records materials that may enable us to form the best possible idea of the climatal conditions of those times. Climate was the cause of glaciation, and if we can make for ourselves a clear conception of the conditions of temperature and rain-fall that accompanied the ice periods, we may be sure that we have half the problem solved.

First, as to the temperature of the glacial periods, we may feel tolerably certain that it was not a time of very low temperature. A very low temperature is inconsistent with a great rain-fall, and, moreover, it is rather negatived by the fact that these ice periods were intercalated among times of very general warmth. We have other evidence that such times had a rather warm climate, which deserves much more attention than has yet been given to it. This evidence we find in the character of the land life that lived near the line of the glaciers during the last ice time. We now know in a general way the character of the animals that lived in Europe during the glacial period, and may make sure from their characters concerning the general conditions of temperature at that time.

If the reader be at all conversant with the distribution of the present animal life of the earth, he will perceive that the species dwelling in the ice time do not at all indicate the evidence of very extreme cold. In the first place, there are two

or more species of elephants, and a number of other forms that are now limited to the tropics. It is true, that the *Elephas primigenius*, or mammoth, was a beast fitted rather for cold than for warm conditions, yet it was a creature that required a large amount of vegetable food, and certainly lived in a country provided with forests. It is a general principle in the distribution of animals that large species of Herbivora only inhabit regions of a fair amount of vegetation, and rather temperate conditions of climate generally. It is therefore a noteworthy fact that the animals that lived on the edges of the ice sheet of the glacial time were larger than their living representatives, even when the forms continue to the present day in such close similitude to their ancestors of the ice time that we term them the same species. They are very generally of smaller size; this is especially the case with our American animals, which have changed less since the glacial period than those of Europe. Our American bisons, deer, beavers, foxes, wolves, etc., appear all to have been larger where they fed near the foot of the ice wall than they are at the present time. We have fortunately a very valuable record of the interglacial life in the closest contact with the ice sheet in the Big Bone Licks of Kentucky. At this locality a set of saline springs form a small morass, in which our larger herbivorous animals sought their supply of salt. As the ground was very boggy, they were often trapped in the mud, and thus left vast quantities of their remains beside the springs. Within a tract of sixty or seventy acres there are probably several thousand skeletons of the mammoth and mastodon, along with the bones of many other species that lived with them. These deposits are probably contemporaneous with the ice sheet in Ohio, and at times this sheet was down to within twenty miles or less of the lick. It is not easy to prove the absolute position of the ice at the time when these licks were the resort of the American elephants, but all that we can learn by the comparison of the districts north and south of the Ohio makes it pretty certain that the greater part at least of the elephants' bones were laid down while the ice lay between the Great Lakes and the Ohio. This abundant life in the glacial time clearly proves that we had a full vegetation, and this is not consistent with Arctic cold.

There are abundant proofs that the glacial period, or at least its closing stages, was a time of much greater rain-fall than at present. The proofs of this are so numerous that a volume might be given to this point alone: we can only indicate the most convincing part of the evidence. Our Dead Sea basins, such as that

of Salt Lake in Utah, are actual rain-gauges. They show the relation of rain-fall to heat in the most perfect manner; they fill with increased rain-fall, and shrink with its diminution. Now the evidence is complete that these basins, of which there are many in Europe, America, and Asia, have all been lowering the level of their waters ever since the close of the last ice time. This, and a great deal of other evidence, that cannot profitably be discussed here, proves that the glacial period left the world with a heavier rain-fall than it now has. This, it might be urged, is not proof, as it is not in itself, that this greater rain-fall existed in the ice time; but when we consider that what we require in glaciation of continental extent is a larger supply of water than is now given to our continents, it is strong presumptive evidence that glaciation was attended by greater precipitation, in the form of snow, than now exists in the regions in question. As Mr. Croll has well shown, the last and all the preceding glacial periods of which we get good evidence are attended by, or intercalated among, periods of considerable warmth that extended to high latitudes. So we may fairly say that glaciation generally means moderate temperature, and very considerable increase of rain-fall, and, furthermore, that it is apt to come in connection with conditions that bring a warm climate close up to the poles. This last point, namely, alternations of temperature, seems to be demonstrated in a complete fashion.

Accepting these evidences concerning the glacial climate, we are able at once to throw away a good part of the hypotheses which have been advanced to explain glaciation. It is clear that the hypothesis of Poisson, which would derive the changes of terrestrial climate from the alternations in the temperature of the spaces through which the solar system swings in its great journey, is useless to us. It is improbable that changes of this suddenness should be brought about by a cause which, if operative at all, acts with such extreme slowness that many geological periods must go by before its effects are felt at all.

It seems also questionable whether the hypothesis that the changes of temperature of the earth's surface are due to the alternations in the composition of the atmosphere can be regarded as capable of explaining the conditions of glacial periods, though there is one way in which their effect might be exercised which has not received the attention of geologists. The presence of a glacial sheet covering near one half of the land surface of the globe would of itself tend to increase the amount of carbonic acid gas in the air, and it is a well-known fact that any increase of this gas would, by resisting radiation, serve to increase the heat

of the earth. This would be brought about in the following manner: by far the greater part of the carbonic acid gas that is taken out of the atmosphere is removed by the action of vegetation. This process of removal is of course proportionate to the area of the forests. If the half of the land were occupied by ice, as it seems to have been during the last and some of the earlier glacial periods, then the drain upon the carbon of the air would be materially reduced. But this gas enters the atmosphere, as far as we know, principally by the volcanic vents that during their period of eruption discharge vast quantities of it, and by the gas-bearing springs which bring up the gas set free by decompositions taking place near the earth's surface. These sources of supply would be of the same power during the glacial period as before, while the agents that tended to withdraw the gas were diminished. This might perhaps lead to the closing of the period of glaciation by bringing about a decidedly increased heat on the earth's surface. I believe it has also been suggested by some of those who believe that the carbonic acid in the earth's atmosphere comes from the celestial spaces, that perhaps at times the supply of this substance is so great that the earth's atmosphere might be suddenly revolutionized as regards its capacity for radiating heat. The essential difficulty with all this class of speculations is that the variations in the amount of carbonic acid gas must be kept within a very narrow range, and it is hard to see how important effects can be produced within that range. We may therefore, on these several accounts, deem this cause alone inadequate to account for any important part of the glacial conditions.

We come now to consider Mr. Croll's theory, the best elaborated of all the hypotheses that have been applied to this problem. There can be no question that Mr. Croll has presented us with a view of true causes that have operated to produce glaciation. The only doubt that can arise is how far they are competent to produce all the effects in question. It must be said for Mr. Croll's view that it receives a very striking support from the fact that between two hundred and forty thousand and eighty thousand years ago we have just such a period of eccentricity as his hypothesis requires. There can be no reasonable doubt that this is the place in time in which we must put the last glacial period. It is also much in favor of his view that this glacial period was not one long unbroken period of ice, but consisted of at least two, perhaps many more, successive periods, in which the ice alternately advanced and receded for very considerable distances. During the recessions, vegetation repossessed the lands up to the edge of the retreating ice,

and during the subsequent readvance the record of this interlude was destroyed, save where the circumstances greatly favored its preservation. Against the theory we may set the following objections: In the first place, it is not entirely clear what would be the effects of the peculiar conditions brought about by the eccentricity of the earth's orbit and the precession of the equinoxes. Mr. Croll has been obliged to heap one hypothesis on another to get the required conditions, yet despite the probability of these several hypotheses, as we now see the laws upon which they rest, some slight, overlooked condition would perhaps serve to negative their action. For instance, if we were denied access to Central Siberia or the region of Mackenzie's River, and yet in some way knew their rain-fall and temperature, we might conclude that glaciers must cover them; but the fact is that a summer of clear skies seems to sweep all the snow of winter away. But this is an objection that will hold to most geological hypotheses as complicated as this is. More weighty objections may be found in the fact that very considerable periods of the earth's history, as, for instance, the whole of the Jurassic section, is almost without traces of anything that can be suspected to be evidence of glaciation, and this although the best-known Jurassic sections lie within the glacial districts of the earth. The same may be said of the sections from the Middle Cambrian to the Carboniferous, a period that certainly required millions of years for its completion, for it includes some of the thickest sections known to us within the glacial areas. We can only remove this objection by supposing that the beds were too far from the shore for the reception of glacial waste. Yet while the much older Cambrian conglomerates are preserved to us, it is hardly reasonable to suppose that these very much newer sections should have preserved no trace of their glaciation. In other words, the eccentricity of the earth's orbit is such a constantly recurring phenomenon that we cannot doubt that each period of one or two million years must have received its effects, and our failure to find any trace of the presence of glaciers in great portions of the earth's history, in which we have many other equally important elements of its history noted for us, must give us pause in accepting Mr. Croll's hypothesis in its entirety. It seems that a yet more grave source of doubt as to the entire validity of Mr. Croll's hypothesis comes to us from the condition of the glaciers in the Southern Hemisphere. As yet we have few and imperfect observations upon them, but all that we have lead us to the conclusion that the ice there is as much in process of retreat as it is in the Northern Hemisphere. Now this, if it be the case, is enough to make us doubt that Mr. Croll's theory is of itself sufficient to

account for glacial periods, for the ice of the Southern Hemisphere should be advancing as that of the North retreats; what one hemisphere loses in ice the other should gain. It is true this objection might be turned by saying that the earth is now escaping from a period of eccentricities, and both hemispheres may have retreating ice. Still the fact remains that the orbit is not near its minimum of eccentricity, and that the Southern Hemisphere should be receiving some effect from this cause. If it is not enough to check the retreat of the ice, then it is hard to believe that the enormous glacial sheets were due to this cause alone.

Mr. Croll's theory is open to yet another criticism; much of its value depends upon the splitting of the equatorial current upon Cape St. Roque. He assumes essentially the same outline and position for this cape during the glacial period that it has at present. This we may perhaps safely allow, but we cannot suppose that such a peculiar geographical feature can have existed for many geological periods. There have doubtless been many times in the earth's history when the equatorial current girdled the earth, and when all the transfer of heat from the equator to the poles depended on the trade-winds, as we have seen in the chapter on the theories concerning the origin of glacial periods. Against all these criticisms Mr. Croll's hypothesis stands, it seems to me, in its essentials untouched. Its propositions clearly rest on a true cause; the only question is as to its being a sufficient cause of anything so wide-spread as the continental ice periods.

The hypothesis that would refer the glacial periods to the changes in the sun's heat has some things that commend it to our consideration. A certain increase of heat would cause an addition to the rain-fall, and would undoubtedly lead to an increase of the glacial sheet in the regions about the pole, and this to an extension of the fog envelope which in all glaciated regions does so much to protect the ice from the sun. In this way the ice sheet might creep south, carrying its peculiar cloudy sky with it, until it attained the dimensions of the glaciers in the last ice time. This hypothesis, which was first suggested by Professor Henri Le Coq, in his little-known work,* has not been sufficiently examined in a critical way to make it safe to rest much upon it. We see at once that the difficulty is that alterations in the sun's heat would have to take place frequently and within narrow limits to accomplish this result, for the average temperature of the earth could never have gone much above or much below its present limits. In a logical point of view this theory is weak, while Mr. Croll's hypothesis, in-

* Des Glaciers et des Climats, par H. Le Coq. Paris, 1847.

asmuch as it rests upon a known fact in the dynamics of the solar system, is stronger. The former hypothesis has to assume that the sun is a star whose heat varies from geological period to geological period. This is an eminently probable hypothesis, yet it is less affirmable than the eccentricity of the earth's orbit. Despite this grave defect, this hypothesis is worthy of attention for the following reasons: it supplies us with an effective explanation of climatal change of the irregularly occurrent sort that the geological record demands; it does not require us to suppose that the record of the glaciers in the Jurassic section or the Middle Palæozoic is lost to us; we have only to say that there were no changes of the solar heat at that time sufficiently great to bring about glaciation. In a word, the hypothesis is less cramping than that of Mr. Croll, though certainly not entitled to the same weight.

We have already suggested one other little-discussed hypothesis. Lyell and others have looked to alterations in the position of the lands as the immediate cause of glaciation. This could not be the case, for the reasons before given. There is, however, an effect due to certain changes, which deserves attention. The Gulf Streams, if we may call all the branches of the tropical stream by this name, depend for their existence on the presence of barriers such as are now afforded by the South American intertropical regions. The accidents of the earth's history may at times lower these barriers. In case South America should ever again sink down so as to allow the equatorial current to pass over its surface, two important consequences would follow: the poles would lose a large part of the heat they now receive, and the equator would gain in temperature what they had lost. Then the trade-winds would have their energy nearly doubled by the increased difference between the temperature of the poles and the equator. They would probably extend as distinct currents up to near the Arctic Circles, and move with greater speed, thus greatly increasing their power over the waters of the oceans. It is even conceivable that the whole system of oceanic currents would be reversed, and their circulation affected by a southward superficial stream from the poles, and an undercurrent of tropical waters towards the Arctic regions. It is possible that a condition of the earth in which the equatorial current was not diverted towards the poles might bring about glaciation, yet the difficulty of carrying much water towards the poles in the cold upper current of the counter trade-winds makes this unlikely.

The nature of the causes involved in the production of glacial periods is as yet

an open question, and it is unsafe for the geologist to commit himself definitely to any of the hypotheses that have been suggested. The most natural course for the student is to try to add something to the facts on which we may hereafter rest some determinate opinion. The most rational attitude for those who have the quality of mind that demands immediate judgment may be expressed as follows: —

There are about half a dozen distinct and powerful causes, each competent to bring about extensive changes of climate, that have probably all been at work on the earth at every stage of its history, — the eccentricity of the earth's orbit, combined with the precession of the equinoxes; the variation of the amount of carbonic acid gas in the air; the variation in the heat of the sun; the variation in the size and position of the oceanic streams, and the variation in the obliquity of the ecliptic. Along with these go doubtless many other lesser or obscure causes of change in the heat of the earth. It is probably somewhat affected by the amount of volcanic activity; the orbit of the earth may be progressively diminishing in diameter, and the distance of the sun from the earth may be increased by the shrinkage of the solar mass. The volume of the atmosphere may be steadily diminishing by being built into the earth's structure; there may be a dozen other factors entering into this complexity of causation we term climate, or even into that simplest of its aspects, the average heat of the earth. At one time one of these sets of powers may operate; at another time another may be so effective as to overshadow all the rest. Out of their collaboration comes the singular general uniformity of the earth's outer temperature, a uniformity that seems indeed wonderful when we consider how many conditions it depends upon.

A period such as the last glacial time may well be due to the cause assigned to it by Mr. Croll, yet at another time, under the same conditions of eccentricity, conditions of oceanic circulation, solar heat, or some other cause may have hindered its action so that continental glaciers may not have been produced. Other glacial periods may have been due in the main to increments of solar temperature or changes in the constitution of the air.

The observer of the development of scientific opinion soon becomes aware that the natural stages of discovery are those through which this problem is now passing. In the beginning comes the partial recognition of a new fact. At first it is confused with other similar things; every step towards its elucidation is due to the conjoint use of the scientific imagination in the framing of hypotheses and of the scientific observation in affirming or denying the conjectures. Generally

the student who forms a particular hypothesis is ever afterwards out of the search altogether. He cleaves to his idol, while fresh men pursue the trail. Finally, when many theories have in turn been held to be sufficient, it gradually appears that they were all, or many of them, in part true, and have to be united to make the whole explanation. In our laboratories we may separate facts and forces, observe them in their separation, and at times refer them to isolated laws; but in the larger laboratory of nature few great events, even the most revolutionary, are to be explained by simple causes. Nature is a web of interlaced forces, and the investigator is never in greater danger of error than when he thinks he has his hand on some very simple truth; the chances are, its unity is only in his own brief vision.

CHAPTER IX.

EFFECT OF GLACIERS ON THE ALTITUDE OF THE LANDS.

Depression of the Land during Glaciation. — Amount of Depression. — Hypothesis of Adhémar. — Objections to It. — Not True in Simultaneous Glaciation about both Poles.— Depression of Lands by Weight of the Ice. — Upheaval south of Glacial Envelope.

WE have reserved to this advanced point of our studies of glaciers the most remarkable of all their effects upon the surface of the earth. It is best to take it up after the other elements of the problem are in a measure clear to us.

It has long been observed by geologists that the Northern regions during the glacial period were the seat of very extensive invasions by the sea. This fact was at first seized upon by a certain school of inquirers as evidence that the glacial work in the transportation of pebbles and the scoring of the rocks had been accomplished by the action of icebergs. Gradually this view has been forced out of the minds of most geologists, until at present there are few who deem it of value.

The amount of the depression varies very much in different countries. The successive advances and retreats of the ice sheet make it hard to determine the precise amount of sinking that occurred in different countries, for the old beaches and terraces formed by the sea during its extension over the submerged lands have been more or less swept away by the later advances of the glaciers. In Southern Europe it appears to have been very variable in amount. In, Wales it was a thousand feet or more, and evidences of a less, though considerable, depression are found in all the regions of Northern Europe that were overlaid by the ice. Just south of the ice this depression seems generally to have been wanting.

In America this depression has not been studied except along the Atlantic shore. Here we have marks of its existence at various heights from the mouth of the Hudson to the north as far as Greenland, but no very definite data exist for the determination of its amount, save at a few points. At its southern boundary the depression apparently did not amount to more than twenty feet; at Boston it seems to have extended up to fifty to eighty feet; on the coast of Maine it was near three hundred feet. In the valley of Lake Champlain it was as much as three hundred and fifty feet; in Labrador it seems to have attained one thousand feet, and in Greenland there are reasons for believing that it amounted to over two thousand feet. This depression of the land brought about by the glacial period continued for some time after the ice passed away.

Only two considerable hypotheses have been framed to account for this singular phenomenon. The first is that of Adhémar, who called attention to the fact that any great accumulation of ice about the poles would cause a dislocation of the earth's centre of gravity, and a new set of levels for the ocean.

There can be no doubt of the worth of this suggestion; but it is easily seen that if this accumulation of ice of the glacial time occurred simultaneously about the poles, then the amount of this displacement of the seas would be very greatly diminished. Under either condition, that of simultaneous or alternate glaciation of the hemispheres, the amount of encroachment of the sea on the shores would be diminished by the mass of water that is taken from the sea and heaped upon the land. If we estimate the ice as having an average thickness of one mile over all the regions glaciated during the last ice period, then the total amount of sinking of the waters of the sea from this cause could not well have been less than from eight hundred to one thousand feet. Allowing this theory to have its value, though in case of simultaneous glaciation of the two hemispheres this value would be small, let us see how far the facts are of a nature to support it. It is clear that the depression produced by the glaciers increases in a general way from the edge of the old ice towards the poles; but it is, it seems to me, equally clear that the increase is not of the regular sort that the theory requires. If a depression of twenty-five hundred feet occurred in Greenland, then the sea level of Central Europe should have been much deeper than appears to have been the case. No marine beds of glacial age appear in Northern France, where they would have been well placed for preservation. The same general facts of irregular subsidence are noticeable when we compare the evidences of depression in Scotland

and this country. The depression about the Gulf of Maine is greater than any we find in England, while according to the theory it should have been less.*

Moreover, the relative depression of the land levels along the American shore are not what they should have been. The depression about Boston was certainly not over one hundred feet, while at Lake Champlain it was near four hundred feet. This difference is greater than should have occurred under Adhémar's hypothesis.

If, during the last glacial period, the ice lay simultaneously on either hemisphere, then we should have had far too little disturbance in the level of the seas to account for this change of level.

There is another set of facts that may have served to bring about this depression, which perhaps will commend itself to the reader as affording, on the whole, more reasonable explanation than the hypothesis of Adhémar. When we attempt to explain the ordinary changes of level of sea and land, we are driven to suppose that the central mass of the earth shrinks, and the outer parts wrinkle upon it. That this is the explanation of the corrugations of the earth's surface which constitute the continents, is well proven. It necessarily follows from this condition of the earth that the continents represent a state of equilibrium of the lateral pressure that tends to urge them upwards, and their own weight that tends to bear them downward towards the centre of gravity. This will account for the constant restlessness of the lands, the ease with which they rise and fall from period to period as geological time goes on. Admitting that this state of equilibration exists in the continents, it follows that the taking of a mass of water from the seas and its imposition on the lands would necessarily tend to flatten their arches and lift up regions beyond the boundaries of the ice. The subsidence of the lands would be proportionate to the weight of the ice, and as the glacial sheet probably thickened towards the poles it would cause a depression of the land by greater and greater amounts as we go towards high latitudes. In a general way this sinking would be proportionate to the thickness of the ice, and this would admit of those irregularities of depression which are hard to reconcile with the theory of Adhémar. This view is much more satisfactory than that of Adhé-

* As the centre of gravity of the ice was probably on the American Continent, it follows that the lines of equal submergence would have run obliquely across the parallels of latitude, the lines of equal submergence extending farther south on the American meridians than they did beneath those of Europe and Asia; but, allowing for this, the criticism seems to have validity.

mar, as it will admit of a considerable diversity in subsidence such as actually exists.

The present condition of the land in countries which have just escaped from glaciation gives support to this hypothesis. There can be no doubt that the lands here are in a state of singular unrest; while shores such as the Mediterranean have maintained their level with remarkable exactness since the Pleiocene period, those of Northern Europe have been frequently disturbed, and the American shore north of Boston is probably still in process of slow elevation at many points. This movement continuing after the ice cap has attained its minimum can only be explained on the supposition that a part at least of the subsidence was due to the weight of the ice. It is not explicable on the hypothesis of Adhémar.

It seems likely that this depression of the northern shores during the last ice period, which continued for some time after the glacier had left the coast line, is probably due to an admixture of these two causes, — the change in the altitude of the sea level, and a certain amount of down-bearing of the land surface by the glacial weight. If it should be proven that the Southern Hemisphere bore at the same time an equal burden of ice, then we should have to believe that the weight of the ice was the principal factor in this subsidence. If, on the other hand, the ice came in succession upon the surface of the two hemispheres, then we must accept the Adhémar hypothesis as probably accounting for the greater part of the submergence.

There is some evidence to prove that there was an upheaval of the country south of the line of the ice during the last glacial period. In New Jersey, Virginia, North Carolina, and farther south, we have some proofs of such movement, but it is hardly complete enough to justify much consideration here. If such elevation took place, it may have been due simply to the diminution in the general level of the seas, caused by the abstraction of the water to make the ice sheet, or it may have been due to an uplift of the surface compensating for the downthrust in the region beneath the surface of the ice, or it may be explained by the change in the altitude of the sea due to dislocation of the earth's centre of gravity, as explained by Adhémar. There are reasons for believing that some cause must have acted to produce a wide-spread elevation of the southern half of North America at a time not far remote from that of the glacial period. The close relation of the animals and plants of the West Indian Islands as well as the deep channels now filled by the deltas of the southern rivers can best be accounted for by supposing that

the sea level has recently stood much lower than it now does in the region about the Gulf of Mexico. This is an interesting field of inquiry, but it would be unprofitable to pursue it here. It is, however, clear that the glacial submergence shows us in a very striking way how many and difficult are the problems brought into the field of geology by the powerful forces of these revolutionary times.

CHAPTER X.

THE EFFECT OF GLACIATION ON THE LIFE OF THE EARTH.

Continuity of Life in Postglacial Periods. — Migration of Species. — Increased Conflict of Species from Crowding. — Return of Species with Retreat of Glacier. — Hairy Mammoth. — Fossil Mammoths of Siberia.

LOOKING upon our earth as a theatre for the development of life, we naturally seek to find what are the effects of these periods of ice upon the history of animals and plants. Here, as everywhere else in this field of inquiry, we find ourselves at the beginning of investigations and not in a position to make any final conclusions. It is at the outset clear that the last glacial period, though doubtless one of the most considerable that the earth has undergone, did not revolutionize life in either the animal or the vegetable kingdoms. We find the same genera and to a certain extent the same species continuing past the break, and we may say the same of several of the great ice times of the past.

The most immediate effect of glaciation is to compel a southward migration of all the species inhabiting the glacial regions, and to pack the faunas and floras of the world into a smaller range of latitude than they occupied before. The animal life of North America, both marine and terrestrial, for instance, lost half its meridional range during the last ice time. It is clear that the tropical regions lost none of their heat, so there is no reason to expect that there was any great change of climate there unless in the way of higher temperature. This condensation of the life of the lands was accompanied by a somewhat slighter crowding southward of the marine life. While the life of the land regions of America moved south over forty degrees of latitude, or about twenty-five hundred miles of distance,

that of the Atlantic was, perhaps, pushed southward quite as far. This movement must have brought about an interesting series of effects upon all the creatures subjected to it. In the first place, the mere act of migration, bringing animals and plants under new conditions, tends to produce in them variations of a striking and important kind. We see this in the case of our domesticated animals; they change as they are transported from one land to another. The creation of variations is a step we need to account for the advance of animals and plants, for we must agree that natural forces to a certain extent preserve the beneficent changes and extinguish the others; so in this way the enforced migrations of glacial times serve to elevate the life by compelling it to journey from land to land.

Besides this direct effect through the variations produced by migration, the movement of animals of diverse kinds into a more limited area tends directly to increase the conflict between the species. This conflict, at all times intense, must be much increased by the concentration of many species in a narrow field. There is reason to believe that the great advance which life has attained in Europe is due, in part at least, to the more effective struggle that has gone on there, on account of the presence of very varied faunas and floras in a contracted field, than we find elsewhere within the temperate zones. Something like the same concentration of life must have taken place in North America during the migrations of the glacial period, when the life of a continent was packed into about one third of the space it now occupies. As the ice went off, the exiled animals and plants slowly won their way back towards the north, but, as we should expect, much changed by the long struggle through which they passed. Many moved slowly in their journey; some species of plants apparently have not yet attained the limits of their northward march, for they will grow much farther north than we find them in the natural forests. The light-seeded plants seem to have gained their northern places more effectively than those whose seeds are too heavy for easy transportation, and which are dependent on chance for their dissemination. Most animals effected their return without difficulty; only some fishes and a few creatures of scant locomotive power have been hindered in their progress. The cray-fishes, for instance, have never found their way past the line of the Connecticut. The region between the Connecticut and Eastern Massachusetts seems to form a barrier they have not been able to overcome. The garpike among the fishes has made its way as far as Lake Champlain, but has not yet gained a place in the more eastern waters. Along our shores the tide of life seems also to be setting northward, but the evidences of this are not very complete.

Considered as an action often repeated in our geological history, glaciation cannot but strike us as a most effective helper in the great struggle for a higher and more perfect life. Through the extensive wanderings to which it compels created things, it constantly proves their fitness to endure the stress of life. Through its action the weak species are the sooner brought into the scales of the stern justice that finds all weakness fit to be punished by death. When we remember that probably very many such periods have done their work we must grant that the effects of glaciation on life have been even more extensive than its physical action upon the surface of the earth.

We cannot take time to discuss the history of all these various forms of mammals that lived during the glacial period; that would be a work in itself. There is one of these, however, that is so conspicuous, and that tells us so much concerning the climate, that it deserves more than a passing notice. The Hairy Mammoth (*Elephas primigenius*) was not only the king of the land beasts during the glacial period, unless we should put our glacial ancestors in that place, but all we know of his history tends to make him the most interesting quadruped of that time. In the closing stages of the glacial period we find him the most widely disseminated of all the large mammals that are known to us. He existed abundantly in America, Europe, and Asia, and though he was associated with several other elephants, none of them approached him in range or magnitude.

As we go back into the glacial time, we have fewer and fewer indications of the existence of this noble beast, yet we have remains enough to make out that he or his immediate ancestors existed at the beginning of that epoch, and that in all its stages he was feeding in the rich forests that seem to have flourished close up to the walls of ice.

In Europe he was certainly a contemporary of man, and we find abundant evidence to show that he was hunted by the barbarians that dwelt in the narrow central field of that continent that the ice failed to occupy. In Asia he seems to have dwelt in great numbers upon the vast plains of Siberia. In that region we are, by a fortunate accident, able to fix the conditions of his existence in a wonderfully complete fashion. When he abounded there, the climate was, as we shall shortly see, as cold as it is at present. The rivers in that country have their sources farther to the south than their main streams, so that the spring-time sends down a torrent of water before the more northern channels are released from their wintry bonds; the elephants seem to have herded together along these

streams for winter quarters, much after the fashion of the moose, reindeer, and other northern mammals, and to have been swept away to the north by the inundations. These freshets carried their bodies to latitudes where the cold was so great that they were frozen in the mud that wrapped them round and covered them to such a depth that the brief summer-times never melted their icy casing. Buried beneath subsequent accumulations of frozen mud, these deposits, containing the carcasses of elephants and other animals (rhinoceros, etc.), accumulated on a subsiding shore to a great thickness. Subsequently they were elevated above the sea level, and now form cliffs of frozen mud. These cliffs are now wasting, from the action of the sun and sea, and as they give way, the buried remains of these ancient creatures fall out of their tombs and tumble down upon the shore. This process has been going on for a vast period, and is so constant that the tusks of these elephants have been articles of constant commerce with China. For centuries they have been taken by the caravan traders, etc., from that ivory-bearing land. A good deal has also found its way to European markets.*

In 1799 the body of one of these elephants was observed by an officer of the Russian government. It seems to have been in a perfect state of preservation, the flesh sound enough to be eaten by dogs; even the eyeballs in this and other specimens were well preserved.†

From these specimens and the abundant skeletons that have been found, we are able to form a very clear idea of this noble beast. In general, he was like our living elephant, but his height was considerably greater than any of his living kindred. The head was more pointed on the crown, and the tusks, in place of extending forward in the sabre-like curve proper to our modern elephant, and all others of

* In 1873 I accidentally learned that a considerable lot of this ivory was on the East and West India Docks of London, the great ivory-market of the world. I made a journey from the North of England to see it, but found to my regret that it had already been cut into merchantable sizes, and in good part delivered to the makers of knife-handles. A small part of the lot, which originally contained, according to the statement of the keeper, about twenty-five tons, was still in the storeroom. All of this ivory had been a good deal damaged by weathering, and was of a bluish-white color, probably due to decomposition, or perhaps to the penetration of the coloring matter from the mud. It had lost some of its animal matter, and consequently cracked along the fibres. Still it was merchantable, and brought somewhere near the price of the cheaper grades of recent ivory. I was informed that in earlier times a good deal of this ivory came to the London market from the ports of the White Sea, but that of late few lots had been recieved. I regret that I did not have time to try to find out more about this interesting commerce, but I hope that some local naturalist will avail himself of this opportunity to learn something concerning this interesting traffic. Even the measurements of a single lot of these tusks would be of great interest to the palæontologist.

† See "The Time of the Mammoth," by N. S. Shaler, American Naturalist, Vol. IV., 1871, p. 154.

his ancient kindred, were sickle-shaped, the points being rounded towards the shoulders.

Curious above all, is the hairy covering with which this creature was armed to meet the Arctic cold. Our modern elephants have scarcely any hair, but the mammoth was covered by a more perfect pelage than any living animal. First, there was a set of close-set bristly hairs, over a foot long, increasing in length on the neck to a sort of mane. Between these were shorter hairs, only three or four inches long, about as closely set as those of our bears. Yet shorter hairs, not exceeding about an inch in length, filled up the interstices; the whole showing that this creature was fitted to his condition.

It is likely that this animal subsisted upon the boughs of the coniferous woods that seem to have lived in these regions. The associated rhinoceros is known, by the fragments of wood found in his teeth, to have lived on such plants. We have already noticed the fact that the men who lived in Europe at the close of the glacial period were in contact with this elephant. There can hardly be a question that the savages living in North America and Asia at the same time were, like their European contemporaries, hunters of this majestic animal. When we consider how much the early training of man depended upon his struggles with the greater brutes; how his skill in fashioning weapons, his courage and power of association with his fellows in using them, grew with the needs of a dangerous and difficult chase, we must look upon the mammoth as one of the important associates of early man.

Beginning the glacial period with man, the mammoth survived all the strange vicissitudes of that eventful period with him, and only disappeared when the earth's climate had settled into about its present conditions. We are at a loss to understand how the death of this species came about; it may, however, be that the mammoth was hunted to death by the flesh-loving peoples of the North, while his feebler and less majestic kinsmen, the Indian and African elephants, had only to contend with less vigorous and less carnivorous peoples.

CHAPTER XI.

RELATION OF GLACIATION TO THE HISTORY OF MAN.

Man before Glacial Period. — Evidence from Central France. — Fossil Man of California. — Proofs of Great Age. — Detail of Evidence. — Proofs of Fossil Man in New Jersey. — Why Peculiar to this Region? — Little Change from Preglacial to Postglacial Man.

AT every stage of their efforts to interpret the history of the earth geologists have found themselves greatly hindered by prepossessions concerning the antiquity, or rather the want of antiquity, of man. Unfortunately this question became apparently involved with the problems concerning man's spiritual nature and his relations to the Creator. It required centuries of struggle to bring educated men to the conviction that the earth was more than six thousand years old. When naturalists, truer to their love of truth than their opponents, finally brought the vast antiquity of the earth into recognition, the doctrine of the recent origin of man still held its ground. Gradually evidence accumulated that carried man farther and farther into the past. The stages in this advance in the understanding of man's history upon the earth constitute the most interesting chapter in geology. We cannot trace it even in outline here. It has resulted in carrying our species farther and farther into the shadowy past, until it finds him in the night of the glacial time, or rather in the evening of the time that closed with that dark period.

The evidence concerning man's relation to the glacial period is divisible into two categories: first, the evidence that connects him with the closing stages of that age; and, second, the proof that would lead us to place his existence before the coming of the ice. Of the first-named class of facts the proof is overwhelming in quantity; of the second, it consists of a few scattered facts, each as strong in

itself as any facts well can be, but they want the effect that accumulated testimony alone can give to the questioner's mind. The connection of man with the closing stages of the glacial period is proven by our finding his bones and the products of his arts buried with the remains of animals that certainly lived near the ice of the glacial period. One of these animals, the hairy mammoth, that certainly survived to the close of the glacial period in Europe, has been delineated by our savage ancestors on a plate of ivory from its own tusks. This

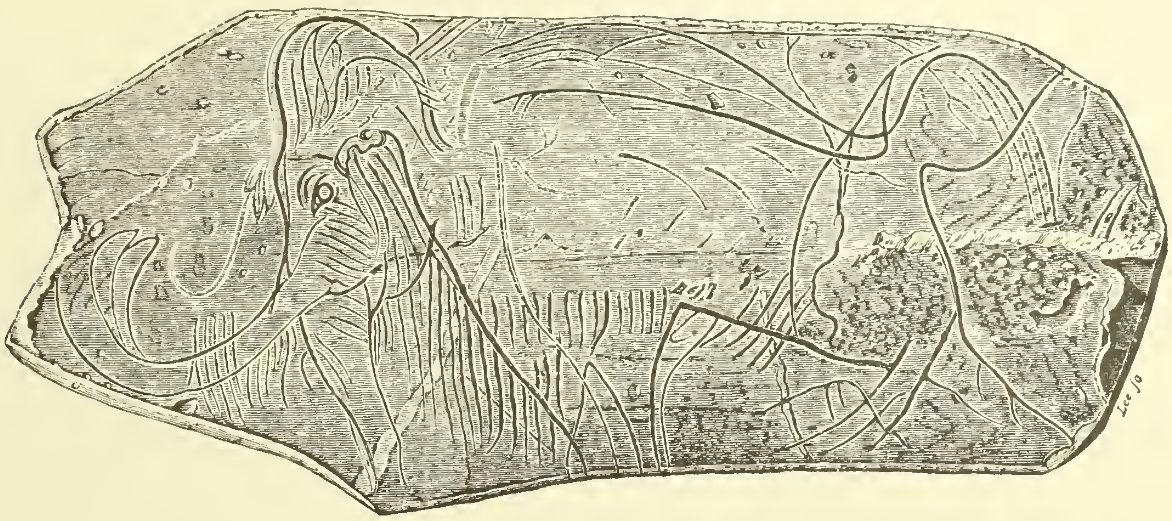


FIG. 18.

DRAWING OF ELEPHAS PRIMIGENIUS ON A PLATE OF FOSSIL IVORY FOUND IN THE OSSIFEROUS CAVERN OF LA MADELAINE, PERIGORD, FRANCE. (FROM LYELL'S "ANTIQUITY OF MAN.")

interesting picture was found in Southern France. There can be no doubt of its authenticity, and it is equally clear that the delineative power of the savage was such as to show that in him lay all the intellectual powers of his kind. One such picture shows us that perhaps tens of thousands of years ago his mental powers were all in existence, and the hand had the deftness that, more than anything else, has made him man. We also find the bodily remains of man in the beds formed while the ice was still moving to and fro in the closing stages of the glacial period.

Finding man struggling with the arduous life of the glacial time, able by his arts to cope with the greatest of the animals of the earth, and to defend himself from the dangers of an Arctic climate, we are ready to trace him beyond the beginning of the last ice period. We cannot conceive man in his first stages as an Esquimaux savage; all his affinities, his hairless body, etc., point to his origin

in a tropical region. So far from beginning his life amid such conditions as the glacial period afforded, we must believe that these beings, struggling with the conditions of the ice time, were but the outliers of their race, and that its populous regions were in more temperate lands.

We are therefore prepared to find that man's history extends much farther back into the past than the close of the glacial period, that it may even antedate that time of struggle. The evidence that leads us to the conclusion that this was the case is, as said before, limited to a few but well attested facts, of which the best are derived from three points widely remote from each other. These points are Central France, the shores of the Delaware River, and the valley of California.

In the European locality, which was the first to be discovered, though the value of the evidence remained long unappreciated, we find the following facts: In the central part of France there is a considerable volcanic tract, where a set of craters, some score in number, now all extinct, have, during a recent geological period, poured out a great amount of lava. In terms of years the period when these volcanoes were in activity is manifestly remote. In the first place, we may note the fact that the sea is now far from these lavas, and that with one exception no volcanoes are now known to be active, that are as remote from the borders of extensive seas or lakes; moreover, from the worn and aged aspects of these volcanic fields we get better proof that a long period has elapsed since they were in process of construction. The rivers have cut deep gorges in their rocks, and atmospheric erosion has worn many of the cones to a very great extent. Nowhere is this erosion more apparent than in the neighborhood of Le Puy, in the province of Haute Loire, near which place the remains of man that now interest us were found. The valley of the Haute Loire is now occupied by a small river, that flows in a channel about three hundred feet deep. The town itself stands upon the ruins of a lava stream, that once filled nearly the whole of this deep valley, but which has been worn down to a few ragged hills by the cutting power of the stream. This sheet of lava came from the volcanoes which lie to the east and west of the town. On the flanks of one of these hills where these craters lay, beneath a part of the lava sheet which once filled this valley, were found the remains of a human skeleton, associated with the bones of a number of extinct animals.

Among the remains now preserved in the Museum of Le Puy is a human cranium of a very fair type of structure. There can be no doubt of its authenticity,

for it is still partly embedded in the volcanic ash in which it lay while beneath the lava. Nor is there any doubt concerning the ancient character of the animals which accompany it. We cannot with certainty say, however, whether these animals are of the period of glaciation or existed immediately before the ice time. The

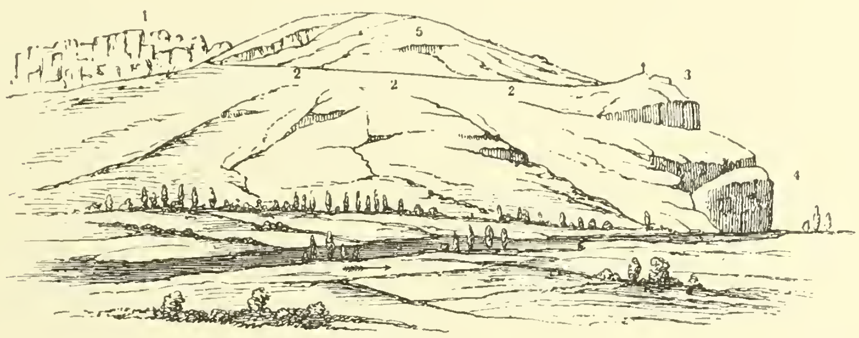


FIG. 19.

MONT DENISE, NEAR LE PUY, FROM THE SOUTHEAST. (FROM SCROPE'S "VOLCANOES OF CENTRAL FRANCE.")

1. Old Breccia Rocks of the Col.
2. Road from Le Puy to Brionde.
3. Croix de la Paille.
4. Orgues d'Expailly.
5. Spot where human bones were found in strata of tuff.

probabilities are that they are more ancient than the glacial period. At this particular point we have nothing to connect these remains with the glacial period; but in the higher valleys of the region to the southwest, near the peaks of Cantal, the distinguished geologist, M. Jules Marcou, has traced the remains of a small system of glaciers which were in existence after the region had acquired its existing topography. It is hard to believe that since these Cantal glaciers were at work the great valley of Le Puy has been cut down to its base. The erosive force of the streams in the two districts is about the same. A reasonable conclusion is, therefore, that the Cantal glaciers represent an access of glaciation that came after the main part of the excavation of the Le Puy valley. This evidence of the Cantal glaciers, taken in connection with the deep erosion of the valley of Le Puy, justifies us in the opinion that these remains are anterior to the main glacial period. The Cantal glaciers must belong to the time of most intense glacial activity. They are south of the extension of the ice in all the lesser periods of its action; so it is only in the deeper stages of the glacial period that they could have been formed. So, if they are antedated by the period of the Le Puy man, that creature certainly lived before the glacial period.

The Le Puy evidence is not as clear as it might be, not in itself conclusive

enough to warrant us in deeming it sufficient to determine the existence of man before the glacial time; yet whoever will examine the facts on the ground will be driven to believe that these remains are older than any other yet found in Europe, and if the observer is well acquainted with the matter of river erosion, he will not hesitate to believe that many tens of thousands of years have gone away since this lava overwhelmed these human remains.

The next evidence in the order of discovery came to us from California. In 1866 Professor J. D. Whitney had his attention called to the discovery of human bones in the gold mines that are excavated in the old river channels of California, channels that have been buried beneath lava streams from a remote antiquity. The conditions of these deposits are so peculiar that they require a special description. This we may well give, for we have here the greatest discovery that has ever been made concerning the antiquity of man.

At the close of the Pleistocene period, probably just before the coming of the glacial time, the volcanoes of this region threw out vast quantities of lava. This lava flowed down the valleys of the Sierra Nevada, filling many of them to the brim. When the streams rearranged themselves after their expulsion from their old ways, they often found it easier to cut new channels beside the lava sheets instead of wearing this lava away. Thus it came about that the old river beds are often found perched on the hill-tops beneath the remains of the protecting volcanic rock.

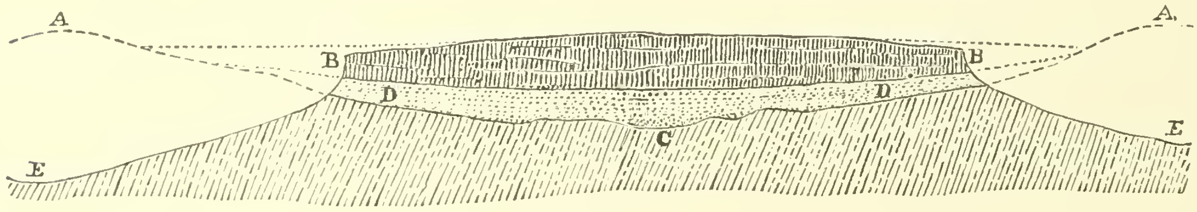


Fig. 20.

General Section of a Lava-capped Table Mountain, California. (Based on a Figure in Whitney's "Auriferous Gravels of the Sierra Nevada.")

A, C, A, original outline of hills and valley.
D, D, auriferous gravels filling old valley.
B, B, bed of lava in old valley on top of gravels.
E, B, B, E, present outline of valleys and table mountain.

In these troughs of the old rivers the miners burrow for the detrital gold they contain, and it is from them that the remains of ancient man associated with extinct animals are obtained. There can be no doubt of the truth of this

discovery,* and it would have to stand as proven even if it were without the corroboration of other discoveries. Fortunately, however, it does not stand alone. Other districts in this State under precisely the same conditions have furnished many specimens of tools worked by the hand of man. They are all of a rude sort, but are unquestionably human implements. Even if the much-laughed-at "Bowers" of "old Missouri" had never had the light of preglacial days through the empty sockets of his eyes, we should know that man had been here before these lava streams filled the old river basins. There can be no doubt that these river basins were closed by the lava before the last glacial period. This region of the Sierra Nevada Mountains was in part ice-covered during the last glacial period, and the valleys contain all-sufficient evidence that the lavas were there, and indeed that the new valleys were to a considerable extent excavated before the ice sheet came.

The following extracts from Professor Whitney's account of the position of the remains will give an idea of the circumstances under which they were found:

"We come now to a county where occurrences of human remains do not seem to have been as frequent as they were in the adjacent Tuolumne; but where one specimen has been obtained which has excited more interest than all the others put together, and which is popularly believed to be the only instance of the kind which has been met with in California. A perusal of the previous and of the following pages will, however, it is thought, satisfy the reader that the belief of the existence of man in that region previous to the cessation of volcanic activity there is not, by any means, backed up by one item of evidence alone. The peculiar interest of the so-called 'Calaveras skull' depends, in good part, on the fact that it is, thus far, the only relic of the skeleton of prehistoric man in California, which has come into the hands of scientific authorities in such a condition of completeness as to give some basis for ethnological conclusions, or, at least, for craniological measurements. Public attention has been so much attracted to the Calaveras skull,† and so much has been said and written about it, that it will be well for the writer to state what he knows with some detail in regard to this find, in order that those who are interested in the subject may have all the facts which are at hand on which to base their opinions.

"The manner in which the skull in question came into the writer's possession is as follows: June 18, 1866, Dr. William Jones, of Murphy's, Calaveras County, a physician of extensive practice in that part of the mining region, and who had been long known to the writer, and for whose veracity and scientific tastes he can personally vouch, wrote to the office of the Geological

* It was the writer's good fortune to hear this evidence substantiating the discovery read before the American Academy. After the reading, having observed that the late Judge Bigelow, Justice of the Supreme Court of Massachusetts, paid very close attention to the presentation of the case, the writer asked him for his opinion of the evidence; he said that he regarded it as sufficient to prove the case in a court of law.

† Calaveras means skulls, and was the Mexican-Spanish name of the river which gave its name to the county, Rio de las Calaveras. Skulls and bones of dead animals are common enough in the Western country, in the vicinity of small streams. A larger collection than usual of such remains at some point on this particular stream may have been the origin of the name.

Survey, at San Francisco, stating that he had in his possession 'a human skull of Indian type, in a good state of preservation, with the exception of the parietal and occipital portions, — the frontal, facial, and temporal being complete, — which was recently found by Messrs. Mattison & Co., in their claim on Bald Mountain, near Altaville and Angel's, one hundred and thirty feet from the surface, and beneath the lava, in the cement, and in close proximity to a completely petrified oak.'

"The State Geologist being absent from the city at that time, Mr. Gabb, the Palæontologist of the Survey, answered Dr. Jones's letter, and requested that the skull might be sent to the office of the Survey for examination, which request was immediately complied with, and the skull forwarded on the 29th of June.*

"On his return to San Francisco, a few days later, the writer examined the skull, and at once proceeded to visit the locality. He saw Mr. Mattison, the principal owner of the claim from which the relic was taken, and heard from his lips the same statement which Dr. Jones had communicated in his letter, with several additional items of information, some of which are of importance as bearing on the question of the authenticity of the supposed find. And here it may be remarked, that nothing is known unfavorable to the credibility of any of the witnesses to the facts in this case; and, were it a question of only ordinary importance and interest, the statements made by them would have been received as being, without doubt, the exact truth. The extreme care, however, with which all the facts, in a case like this, should be weighed, must be my excuse before these gentlemen for seeking to sift the evidence, and endeavoring to ascertain, by comparison and putting together of various circumstances, whether there were any flaws in their statements, or whether any reason could be found for doubting the exactness of the information given by them.

"Mr. Mattison, on being questioned, stated that he took the skull from his shaft in February, 1866, with some pieces of wood found near it, and, supposing that it might be something of interest, carried it in a bag to the office of Wells, Fargo, & Co.'s Express, at Angel's, and gave it to Mr. Scribner, the agent, also well known to the writer as a man of intelligence and veracity. He stated, on being questioned in regard to the appearance of the skull when it was brought to him, that it was so imbedded in and encrusted with earthy and stony material that he did not recognize what it was. Mr. Mattison had previously made a similar statement, saying that when he found the object he thought it to be a piece of the root of a tree, only a portion of the frontal bone being visible. Mr. Scribner's clerk cleaned off a portion of the encrusting material, discovered that the article in question was a human skull, and, shortly after, gave it to Dr. Jones, who was well known in that region as an enthusiastic collector of objects of natural history, and in his possession it remained for some months before it was placed in the writer's hands.

"The skull is by no means a perfect one, as the whole of the parietal and nearly the whole of the occipital, as well as a large part of the right half of the base, are missing. The line of fracture through the base is from the right temporal fossa through the opening for the spinal cord, leaving its fore part, and ending about an inch and a half behind the left ear. The frontal bone is nearly entire. A fracture extends across the upper jaw, a short distance below the

* This skull was temporarily intrusted to the writer; and, after the discontinuance of the Survey, given to him by Dr. Jones.

orbits, otherwise the bones of the face are in most respects complete. This describes the appearance of the skull as it now exists. When delivered into the writer's hands its base was imbedded in a conglomerate mass of ferruginous earth, water-worn pebbles of much altered volcanic rock, calcareous tufa, and fragments of bones. This mixed material covered the whole base of the skull and filled the left temporal fossa, concealing the whole of the jaw. A thin calcareous incrustation appears to have covered the whole skull when found; portions of it had been scaled off, probably in cleaning away the other material attached to the base.

"Nothing was done to the skull to alter its condition in any way, after it came into the writer's hands, until it had been examined by Dr. Wyman, when we together carefully chiselled off the foreign matter adhering to its base, so as to fully expose the natural surface of the skull, leaving it in its present state.

"On exposing the jaw, the skull was found to be that of a very old person; as the teeth, with the exception of a single root of a molar on the right side, have disappeared. All the alveoli in front have been wholly, and those on the sides partly, absorbed; in consequence of this, if any peculiarity of the jaws existed, it is no longer to be recognized.

"In cutting away the mixed tufa and gravel which covered the face and base, several fragments of human bones were removed; namely, one whole and one broken metatarsal, the lower end of a left fibula, and fragments of an ulna, as well as a piece of a sternum. These bones and fragments of bone might have belonged to the same individual to whom the skull had appertained; but, besides these, there was a portion of a human tibia of too small size to be referred to the same person. There were also some fragments of the bones of a small mammal. Under the malar bone of the left side a small snail shell was lodged, partially concealed by one of the small human bones which was wedged into the cavity. This shell was recognized by Dr. J. G. Cooper as *Helix mormonum*, a species now existing in the Sierra Nevada. Cemented to the fore part of the roof of the mouth was found a circular piece of shell four tenths of an inch in diameter, with a hole drilled through the centre, which had probably served as an ornament. Several very small pieces of charcoal were also found in the matter adhering to the base of the skull.

"On chemical examination of a portion of the skull by Mr. Sharples, it was found that it had lost nearly all its organic matter, and that a large portion of the phosphate of lime had been replaced by the carbonate. In other words, it was in a fossilized condition. The following are the results of the analysis: —

Phosphate of lime	33.79
Carbonate of lime	62.03
Silica	1.44
Oxide of iron	.81
Carbonate of magnesia	1.86
Water and organic matter	trace
	99.93

"The skull having been coated with wax to protect it, the analysis was made on a piece which had been treated with ether to remove any still adhering particles of this substance: this also took up any organic matter remaining over from what originally existed there. A separate examination of another piece of the skull showed, however, that only a trace of this existed.

"Such are the facts concerning the Calaveras skull, in regard to which there can be no dispute. It remains to describe the geological position in which it was said by Mr. Mattison to have been found, and then to see how the facts observed agree with his statements, and especially how far the condition and appearance of the skull itself lend plausibility to the theory — widely circulated and believed in — that the find is 'a hoax.'

"According to Mr. Mattison's statement, the skull was taken from a shaft which he himself had sunk on the northwest slope of Bald Hill, at a distance of just half a mile northeast of Altaville, which is about a mile and a quarter northwest of Angel's, the outcrop of the Great Quartz Vein intersecting the road between the two places, and running close to and nearly parallel with it. All along the region adjacent to this road, on the northwest, is a series of moderately high table-topped elevations, which rise from 300 to 400 feet above the bed of Angel's Creek, just below the town of that name. Bald Hill is the most conspicuous of these hills, and it runs in a northeasterly direction for half a mile, its culminating point being 388 feet above the creek at Angel's, which itself is 1,380 feet above the sea-level. The higher portion of all these elevations is made up of volcanic and detrital materials, consisting, so far as could be seen, of alternations of more or less consolidated volcanic ashes and of gravel beds. The volcanic deposits are either white or dark bluish-gray in color; the whiter varieties being very fine-grained and pretty solidly compacted together. It is what is usually called 'white lava' by the miners, and is probably rhyolitic in character. The deep gravels in this vicinity do not seem to have been profitable to work, and all the excavations made about Bald Hill had been abandoned at the time of the writer's visit; and, so far as known, have not been resumed. The opportunities for getting an exact section of all the beds as in this elevation have therefore not been satisfactory. Mr. Mattison, however, gave the following as the section of the strata penetrated in sinking his shaft, which he said was 153 feet deep to the bed-rock: —

	Feet.
1. Black lava	40
2. Gravel	3
3. Light lava	30
4. Gravel	5
5. Light lava	15
6. Gravel	25
7. Dark brown lava	9
8. Gravel	5
9. Red lava	4
10. Red gravel	17
Total	153

"The skull, on Mr. Mattison's authority, was found in bed No. 8, just above the lowest stratum of lava. . . .

"Having in the preceding pages set forth somewhat in detail the condition of the skull when received from Dr. Jones, and described its appearance after being freed from the débris in which it was imbedded, and having shown what the materials were thus found associated with it, it remains to add a few remarks in elucidation of the question how far the condition and appearance of this skull and all the facts connected with it justify us in believing that

the statement of Mr. Mattison in regard to the place in which it was found may be accepted as true.

"The skull, being as nearly deprived of its organic matter as fossil bones found in the Tertiary usually are, and having had a large portion of its phosphate replaced by carbonate of lime, is undoubtedly *a fossil.* Chemical analysis proves that it was not taken from the surface, but that it was dug up somewhere, from some place where it had been long deposited, and where it had undergone those chemical changes which, so far as known, do not take place in objects buried near the surface. In view of these undoubted facts, the absurdity of the statement previously quoted in regard to the placing of the skull in the shaft 'as a hoax' to be played off on the 'anti-Scriptural' miner becomes apparent. The miners who are supposed to have done this clever trick must themselves have obtained from somewhere the object thus used; and as all the diggings in that vicinity are in the gravels intercalated between the volcanic strata, it becomes, really, a matter of but little consequence, from a geological point of view, from whose shaft the skull was taken. The following are the considerations, then, which lead us to put confidence in Mr. Mattison's assertions as to his having taken the skull out of his own shaft, and from the position already indicated.

"In the first place, the locality and the neighborhood were several times visited by the State Geologist, and also by three of his assistants, and by several of his personal friends not connected with the Geological Survey, and to all these Messrs. Mattison and Scribner have given exactly the same statement in regard to the finding of the skull. All of these gentlemen have returned from the place strongly impressed with the idea that there was no mistake, and certainly no intentional misstatement, on the part of either of the principal parties whose names are associated with the find. Messrs. Mattison and Scribner have uniformly told to all the same story, and nothing has developed itself as offering a motive to either of these gentlemen to enter into a combination for the purpose of deceiving individuals or the public. The skull remained on and near the place where it was obtained for several months after it was discovered; and no doubts were expressed by any one as to the good faith of the parties concerned, until after it had been sent to San Francisco and had been much written about in the newspapers. At the time of the writer's first visit to the region, after the discovery had been made, the miners were evidently entirely unaware of the geological significance of the find. Similar ones had been made before, in repeated instances, and in various districts in the neighborhood, without exciting, so far as it appears, any special interest. It is giving the miners far too much credit for geological knowledge to believe that they would recognize the importance of such a discovery. Much less would it have occurred to them to see anything 'anti-Scriptural' in it.

"Again, evidence in regard to the skull obtained from an inspection of the ground in the shaft about the spot whence it was said to have been taken is, as yet, wanting, as the excavation has remained filled with water during the whole time since the skull came into the writer's possession, and it has never been in his power to visit the place at a time when the shaft could conveniently, without considerable expense, be emptied of its water. It was his intention to have this done; but circumstances have rendered it impossible that the desired end should be attained. Mr. Mattison has always said that he expected to resume work in the shaft at some future, not distant, time, and that he would give notice whenever he did so, and that a full opportunity should be afforded of making a careful inspection of the vicinity.

"The appearance of the skull when it came into the writer's hands, and especially its

appearance when obtained by Mr. Scribner, whose statements may be considered as beyond suspicion, shows that this is not an ordinary skull picked up at random in order that it might be palmed off as a curiosity on an unsuspecting 'Eastern geologist,' or even an 'anti-Scriptural miner.' The skull was unquestionably dug up somewhere, and had unquestionably been subjected to quite a series of peculiar conditions. In the first place it had been broken, and broken in such a manner as to indicate great violence, as the fractures go through the thickest and heaviest parts of the skull; again, the evidence of violent and protracted motion is seen in the manner in which the various bones were wedged into the hollow and internal parts of the skull, as, for instance, the bones of the foot under the malar bone. The appearance of the skull was somewhat such as would be expected to result from its having been swept, with many other bones, from the place where it was originally deposited down the shallow but violent current of a stream, where it would be exposed to violent blows against the boulders lying in its bed. During this passage it was smashed, and fragments of the bones occurring with it were thrust into all the cavities where they could lodge. It then came to rest somewhere, in a position where water charged with lime salts had access to it, and on a bed of auriferous gravel. While it lay there the mass on which it rested was cemented to it by the calcareous matter deposited around the skull, and thus the base of hard mixed tufa and pebbles which was attached to it when it was placed in the writer's hands was formed. At this time, too, the snail crept in under the malar bone, and there died. Subsequently to this the whole was enveloped by a deposit of gravel, which did not afterwards become thoroughly consolidated, and which, therefore, was easily removed by the gentlemen who first cleaned up the specimen in question, they only removing the looser gravel which surrounded it.

"Now, such is the condition of things and the chain of events through which the skull passed, as vouched for by its own appearance when it left Dr. Jones's hands, and by the perfectly reliable statements of Messrs. Jones and Scribner.

"How does this compare with Mr. Mattison's statements as to the position of the skull? And this is a question of great importance, as, if this gentleman told one story and the skull another, we should not doubt which authority to accept. If, on the other hand, there is no discrepancy in the evidence thus furnished by the dead and the living, then we have here a very strong corroborative link in the chain of testimony, going to show the genuineness of the find.

"Mr. Mattison told me that he with his own hands took the skull from near the bottom of bed No. 8 [in the section given on page 130], and that it was found lying on the side of the channel with a mass of drift-wood, as if it had been deposited there by an eddy of the stream, and afterwards covered over in the deposit of gravel by which bed No. 8 was formed. Now here seems to be a very satisfactory coincidence between the statements of Mr. Mattison and the facts revealed by the condition of the skull itself. Indeed, the coincidence is as complete as could be desired, and in view of these facts it seems very difficult not to accept the statements made by the gentleman in question as authentic.

"We have the independent testimony of three witnesses, two of whom were previously known to the writer as men of intelligence and veracity, while in regard to the third there is no reason for doubting his truthfulness. Each one of these gentlemen testifies to some points in the chain of circumstantial evidence going to prove the genuineness of the find. No motive for deception on the part of Mr. Mattison can be discovered, while the appearance of the skull itself bears strong, though silent, testimony to the correctness of his story.

"The following is Dr. Wyman's notice of the craniological peculiarities of the Calaveras skull: —

"'The volume of the frontal region is large, so that if the skull were viewed from above, the zygomatic arches would be nearly concealed. As a large part of the occiput is destroyed, it is uncertain whether the head was long or broad. The face is somewhat deformed, the left orbit being smaller, and the left cheek higher than the right, thus giving the whole an unsymmetrical appearance. The ridges over the orbits are strongly marked, and the lower border of the opening of the nostrils is not sharp, but, as in some of the crania of many savage races, is rounded, and the malar bones are prominent. The strongly marked borders of the orbits are the most striking features of the fragment.

"'Extended comparisons of crania clearly show that the range of variation in the individual characters of a given race is quite large. This is well illustrated in the results obtained by the eminent American craniologist, Dr. Meigs, in regard to the ratio between the breadth and the length among the American aborigines, in one and the same race, some having the long and others the broad head. In a series of skulls from one of the Hawaiian Islands we have found the long and broad heads in nearly equal proportions, the breadth varying from 0.72 to 0.94 of the length. As other features offer similar differences, any conclusions based upon a single skull are liable to prove erroneous, unless we have sufficient grounds for the belief that such a skull is a representative one of the race to which it belongs. If this consideration had been kept in view, much useless discussion in regard to the celebrated Neanderthal skull might have been avoided. We have no sufficient reason for assuming in the present instance that the skull is a representative one; and, in view of this circumstance, the results given in the following table must be considered as applicable only to an individual, not to a race. Future discoveries can alone decide its real value.

	Breadth of Cranium.	Breadth of Frontal.*	Frontal Arch.	Length of Frontal.	Height of Cranium.	Zygomatic Diameter.
22 Esquimaux	134.5	94	296.5	126.6	135	137.6
5 from Alaska	133.5	92.8	285.5	121.8	129.5	132
11 from different parts of California	150.5	93.5	260	117	120.8	134
3 Digger Indians	136.6	88.3	280	119	120.3	141.5
Fossil skull	150	101	300	128	134†	145

(The measurements are in millimeters.)'" ‡

It is not certain whether the Calaveras man was buried before the man of Le Puy, but it is clearer that the burial of the Calaveras remains took place before the last glacial period than is the case with the remains at Le Puy. Professor Whitney thinks that the Calaveras man belonged to the Pleiocene age some time before the glacial period began to appear.

* This is the breadth of the frontal at its narrowest part when the skull is viewed from above.

† Measured from the anterior edge of the foramen magnum to the level of the top of the frontal, and an inch behind it on the inside.[1]

‡ The Auriferous Gravels of the Sierra Nevada of California. J. D. Whitney. pp. 267–273.

[1] These measurements can, of course, be only considered as approximations; the fragmentary condition of the skull must be taken into consideration in this connection.

It is clear that the assemblage of life associated with these remains is of a rather more southern type than that which accompanies the specimen of Le Puy. This may be of value, as indicating a somewhat later age at this last-named point. Too much weight should not, however, be assigned to this.

The last observed remains that clearly point to the existence of man before the last glacial period are those found at Trenton, N. J., on the banks of the Delaware. At this point we have a large area covered by the table drift or glacial matter that was rearranged under the water of the sea during or immediately after the close of the glacial period. This bench of drift has its surface about twenty feet above the level of the high-tide mark. Its internal character is exactly like the similar deposits occurring in other districts, — a loosely, irregularly stratified mass of glacial waste, the pebbles rarely exceeding a few inches in diameter, and mostly deprived of their scratches by water action. In this district Dr. C. C. Abbott found some specimens of rudely worked stone implements, bearing the general character of the so-called celts, that is, rough tools that, inserted in handles or held in the hand, were used by the primitive races as axes or what not. At first these discoveries were few in number, and their shape so rude that they seemed possibly to be cases of natural chipping. The skilful and untiring search of the discoverer has now accumulated these stones to the number of hundreds, and it is impossible to resist the conviction that they are, in fact, the products of a very rude human art. No bones of other animals, no other tools of any sort, have been found in this deposit. It is, as such deposits generally are, essentially without trace of organic remains.

From a rather incomplete study of the ground, the only view I could take of these remains was that they were scattered on the surface of the earth to the northward before the last glacial period; that they were thrust before the glacier during its period of greatest extension, and deposited in the beds where they now lie by the action of water while the shore underwent a slight submergence. We cannot regard the advance of the ice that brought them to this place as having occurred during the second or any late stage of the glacial period; for these advances did not bring the ice so near its farthest point of southward march as this locality. Nor can we deem it probable that the implements were, dropped into the deposit as it was formed under water by some race of fishermen. Such tools could only have been of use in something like seal-fishing, and this idea is negatived by the absence of all signs of life in the deposit as well as by the great abun-

dance of the tools. Several hundred of these have been found along escarpments that do not altogether amount to a mile in length, and there must be tens of thousands of them in each square mile of the deposits of this age that cover the country about Trenton. If this hypothesis concerning the origin of these implements be true, then the surface of country that furnished this waste must have been amazingly strewn by this class of remains. Although the valley of the Delaware has been a favorite place for the aborigines of this continent for many thousands of years, nothing like such an abundant evidence of their existence would be furnished by their stone tools if the present surface of the country were scraped away and laid down in such terrace deposits. In any view we may take of the facts, we must confess that these remains are artificial; on this point we now have no basis for doubt. We must also allow that either during or before the glacial time this region was dwelt upon by men for a longer time than it has been since the ice passed away.

It may be asked why it is that the abundant table drift in regions farther north has supplied no such evidences of implements as we find on the southern edge of this ice sheet. It seems to me that the following conditions may perhaps explain this fact. When the glacial sheet swept over New England it for a long time cast its débris into the sea, so that the materials contained in the soil, in the peat bogs, ponds, and other receptacles of human implements that may have existed here before the ice came, would have been carried out into deep water. The table drift there was composed of materials worn from the rocks long after the ice sheet had swept away all traces of the original soil surface and every other deposit that could have contained human remains. It is only where the ice sheet laid down its first sweepings of the surface upon the land, or in shallow water which has since given up its deposits to the land by re-elevation, that we can expect to find any traces of preglacial human remains. If this position be rightly taken, the failure to find such remains in the drift of New England, where we know the ice has extended much beyond the shore, is to a certain extent a corroboration of the theory that has just been advanced to account for their presence in the beds at Trenton. From this view the discovery of Dr. Abbott leads us to look with singular interest to the study of frontal drift in the glaciated countries. More or less clearly this frontal drift must extend along a long line in this and other countries. In it we may fairly hope to find at many other points something like the remains that have been secured by Dr. Abbott's labors in a small field.

When we consider that little is ever found that is not sought for with the help of knowledge, and that our inquiries into the glacial deposits have rarely been undertaken with eyes open to the value of their records, or the history of early man, we may fairly consider that the three or four very clear bits of evidence we have already secured are but the beginnings of the testimony that is to prove the presence of man on the earth before the last glacial period.

It is not, however, in glaciated countries that we can ever hope to carry back the history of our race towards its beginnings. That region has been the seat of too intense erosion for us to hope to find any complete record of land life. If we are ever to track the animal man back to his beginning, the record will be found in more southern lands. Yet these glacial records enable us to take one long step, and to say that our species probably was in existence at least a quarter of a million years ago.

It is a noteworthy fact that the social condition of man, as exhibited in the state of his arts that have come down to us from the preglacial time, show that little change came over his conditions in the long period that elapsed between the man of Calaveras and the Europeans of the stone age. It is impossible to believe that this time was not very great, if we adopt the hypothesis of Mr. Croll. We must allow that at least two hundred thousand years, or forty times the term of recorded history, lie between these two groups of men. Yet they seem by their arts, that supreme test of human conditions, to have been on the same general level of development. Both had made the great step forward that lifted the species into its manhood; both were tool-users; both had learned to shape stones and perhaps to use fire: but neither had made the next great step in civilization by learning to subdue the more fusible metals to their use.

What was the power that, some ten thousand or so years ago, suddenly lifted this ancient savage man out of his long sleep and set him then moving swiftly on his upward way? It could not have been the contending with the difficulties of his environment, for he had lived unchanged through the most hazardous times that the world ever knows, and only began his higher development when the world had returned to something like its usual order. It seems to me that we have, in this most singular of all the changes that have overtaken life, a phenomenon of development that is of a different order from anything else that life presents to us. To see the full magnitude of the problem, the reader should bear in mind the fact that the Calaveras man was completely man. The excessively large skull,

with the brain exceeding the demands that the habits of the mind put upon it, all the initial habits of tool-making which seem to afford the basis of human advance, were there, yet the man lay dormant for thousands of centuries without taking one other upward step.

We have just attributed to man an antiquity of probably not less than two hundred and fifty thousand years. To justify this estimate of his antiquity, we must give the reasons for supposing that the last glacial period came upon the earth about that number of years ago.

If we accept Mr. Croll's hypothesis, which, as mentioned before, is the most probable of all the principal causes that have been assigned for the last glacial period, we are able to assign the time of the beginning of that ice period with great accuracy, as will be seen by the appended list of periods of great eccentricity.

Eccentricity of the Earth's Orbit for Intervals of 10,000 *Years, from* 250,000 *Years ago to the present Date.*

No. of Years before A. D. 1800.	Eccentricity of Orbit.	No. of Years before A. D. 1800.	Eccentricity of Orbit.	No. of Years before A. D. 1800.	Eccentricity of Orbit.
250,000	0.0258	160,000	0.0364	70,000	0.0316
240,000	0.0374	150,000	0.0332	60,000	0.0218
230,000	0.0477	140,000	0.0346	50,000	0.0131
220,000	0.0497	130,000	0.0384	40,000	0.0109
210,000	0.0575	120,000	0.0431	30,000	0.0151
200,000	0.0569	110,000	0.0460	20,000	0.0188
190,000	0.0532	100,000	0.0473	10,000	0.0187
180,000	0.0476	90,000	0.0452	A. D. 1,800	0.0168
170,000	0.0437	80,000	0.0398		

According to these computations glaciation began about two hundred and forty thousand years ago, and must have begun to pass away about eighty thousand years ago, and the Pleiocene time lay in the ages between two hundred and forty thousand years ago and the remote period of great eccentricity that occurred in a yet more distant time. It is in the Pleiocene time that the men of Trenton and Calaveras probably lived. If we reject eccentricity, or the principal factor in the last ice time, we are then driven to general computations based upon the erosion effected by the last glacial period. To these we cannot give a certainty in terms of years. We can only feel sure, after computing the depth of the erosion that has taken place in certain districts, that the time must have been very great. We find at the outset, however, the difficulty, which we cannot yet see any means of clearing away, of separating the erosion of the last glacial period from that of periods that came before. So we can only make use of the moraine matter that lies in the frontal glacial heaps such

as those of Long Island, N. Y. Estimating from these, we obtain some not very satisfactory evidence to show the long duration of the last glacial time. Allowing that even one tenth of the eroded matter of the glacier escapes to the front, this mass would perhaps represent a sheet twenty-five feet deep over the country to the north for two hundred miles. Assuming that the erosive action of the ice was as much as one tenth of one inch per annum on the average of this surface, we should have only a period of two thousand years represented by the time when the glacier lay at the present position of Long Island. This is a very brief time, nor can we fail, on the same basis, to get very short periods for the time comprised in the several stages of retreat. Considering the profoundly scored character of our rocks, many single scratches being an inch or more in depth, we cannot believe that we have overestimated the rate of wear of the more exposed regions. The probable error is in the percentage of rocks that escaped from the front of the glacier in a form not readily carried away by marine currents. We are absolutely at a loss to fix the relative amount of glacial waste that is ground up into fine mud or sand and so made free to be carried by the sea, and that which journeys on to the front of the glacier as pebbles. It is likely, however, that nearly as much rock in the shape of pebbles would be worn out in effecting the erosion of the surface over which the ice was moved, as would be worn from that surface; so the amount of waste left to us from the glacial period may be only a very small fraction of the total worn from the surface of the land.

Thus we see that if we are driven away from the hypothesis of Mr. Croll, there seems scarcely any basis for computing the duration of the last glacial period. If due to the change of the sun's heat, or any other cause, it must remain essentially an incalculable element; we can only assume for it an unknown but presumably long duration.

CHAPTER XII.

THE MOVEMENT OF GLACIERS.

Absence of Early Observations. — Beginning of Inquiry. — Charpentier. — Agassiz. — Forbes. — Tyndall. — Croll. — Pressure Melting. — Movement of Snow in New England. — Review of Phenomena. — Review of Hypotheses. — Continental Glaciers. — Their Conditions. — Possible Explanations of their Movement.

NOTHING shows more clearly than the history of glacial discussion the incapacity of the human mind for observation during the first seventeen hundred years of our era. The glaciers of the Alps must have often met the eyes of scholarly and reflective people during these centuries. The Romans held the larger part of Switzerland for centuries, and, as was their habit elsewhere, they probably brought the ice of these streams down to their towns and villages in the lowlands. During the revival of learning, a good many scholars lived within sight of these eternal snows that fed the glaciers, yet from none of them, ancient or modern, do we find a word concerning that singular movement of the ice streams, which, it would seem, must have caught the eye in the least degree accustomed to inquiry.

This want of observations upon glaciers can only be explained by the general lack of interest in the phenomena of nature, that is such a striking feature in the first stages of our modern civilization. From the fall of the Roman Empire to the eighteenth century there are only two or three men known to us who would have looked with penetrating eyes upon their strange shapes. Leonardo da Vinci, Albertus Magnus, and perhaps Bacon, would have questioned them if they had been brought before their eyes. But even these far advanced and essentially modern minds were without that real love of nature which is the most modern of all intellectual attributes. So the intellectual men before the eighteenth century were by habit cut off from the opportunities of such inquiries.

It is not until the time of De Saussure's exploration of the Alps* that we find men becoming conscious that there was a problem in these glaciers that deserved solution. It is likely that the minds of naturalists were first turned to these questions by the opinions of the mountaineers whom they employed as guides. There can be no doubt that the upland Swiss peasants long had been familiar with the phenomena of glacial motion. The passable character of many of their mountain ways, the value of many a mountain pasture, depends upon the changes brought about by the varying motion of the ice. When naturalists began to question these men concerning the glaciers, it was evident that they long had known that the glaciers were constantly moving forward as their front parts melted away.

It is to De Saussure that we owe the first hypothesis concerning glacial motion, if we may give the name hypothesis to any conjecture as rude as his scantily expressed idea. Clearly observing the downward movement of the ice, he suggested that the motion was a process of sliding downwards, and that it was facilitated by the melting of the bottom ice of the glaciers where it was in contact with the earth, brought about by the internal heat which De Saussure apparently believed competent to melt the water that escapes in the subglacial streams. It hardly appears possible that this acute mind, to whom all the phenomena of the mountains were singularly attractive, should have failed to give a more rational statement than this. We are forced to believe that this statement does not represent his conclusions. He must have seen the river-like action of the glacial stream, that is certainly inconsistent with anything like a simple sliding of the ice down the steep.

About 1840 there came a sudden increase in the interest with which all problems of terrestrial physics were viewed, and this movement brought a number of distinguished naturalists to the study of glaciers. Attention was directed to this subject by some recent studies concerning the former extension of glaciers. The mountaineers of Switzerland — the admirable race that has furnished the modern guides of that country, to whom we doubtless owe the first discovery of glacial motion — saw, first of all, that the heaps of moraine matter in the valleys were proofs that the ice had once extended much farther than at present. These rude observations were at this time taken up by the local students. Venetz, a government officer of the old salt-works at Bex, and Charpentier, a Lutheran pastor at the village of Les Ormonts, were among the first in the field.

* Voyages dans les Alpes, par H. B. de Saussure. Neuchâtel, 1803.

It is principally to Charpentier that we owe the first studies upon the former great extension of the Rhone glacier beyond its northern valley and across the plains of Switzerland. This proposition, which he fully discussed in 1841,* made it clear to all naturalists that the glacial problem was worthy of the fullest attention, as it might throw light on the former conditions of the earth's surface. M. Charpentier did not limit his studies of glaciers to the matter of their former extension; he also propounded a theory concerning their motion, which, though untrue, has the advantage over the view of De Saussure, that it takes account of the more complicated parts of the problem. Charpentier's idea was subsequently elaborated by a more celebrated naturalist, and for a time it promised to give a reasonable explanation of the motion. It is, in effect, that water taken into the interstices of the glacier by day was frozen by night, and, expanding in the process, urged it down the slope.

At this time Agassiz, who had hitherto been occupied by his illustrious labors in the department of zoölogy, turned his eager attention to the problem of glacial motion, which he, first of all, saw as a question destined to throw light upon the past history of the earth. His first effort was to find the real nature of the movement of the ice masses by observations of an accurate sort upon their surface. In this work he was the pioneer, for all previous investigators had limited their observations to the mere inspection of the glaciers, and not a single accurate measurement had been made. After some summers of reconnoissance and preliminary trial, he devised a critical series of experiments, which laid the foundation for all subsequent studies on the motion of glaciers. This plan consisted essentially in the planting of stakes upon the glacier, which should be left free to move for a season; then, by observing the change in their place with reference to fixed points on the mountain side, the rate of movement of the whole glacier and its several parts could be determined with accuracy. After the first winter Agassiz had the melancholy satisfaction of finding that he had overlooked the hitherto unnoticed phenomenon of ablation, and that the melting away of the ice constantly brings down the surface of the glacier when it lies below the snow line. His stakes were all overthrown, and the work of a season essentially lost, at least as far as the principal inquiry was concerned. The following season, however, he set to work planting these stakes deep enough to assure their standing until his next vacation would permit the final determination of the problem. As chance would have it, among the many naturalists who received the hospitality of his camp on the glacier, was one who was fully possessed of all the resources of the

* Essai sur les Glaciers, etc. Lausanne, 1841.

physicist and surveyor, Professor J. D. Forbes, to whom this subject was hereafter to owe so many and valuable studies. While the guest of Agassiz, Professor Forbes made his first acquaintance with existing glaciers. Owing to his superior training in the branches of learning that this peculiar problem called for, he soon saw that the method that Agassiz was using was, by a slight modification, capable of a more speedy solution than his Swiss host could obtain under the conditions of his experiment. Agassiz planted a row of stakes across the glacier, but proposed to wait, with the patience that characterized his mind, until after a winter to read the answer he sought. Mr. Forbes saw that with a transit or a theodolite he could, in a few days at most, see how the stakes were moved, and so anticipate the results his host was seeking. With this plan in mind he went to the Mer de Glace, set up a line of stakes in the precise fashion devised by Agassiz, and within a month proved that the ice moves most rapidly in its middle parts, and not, as had been supposed, more quickly upon the sides of the stream; this result he hastened to make public. There can be no question that this was one of the most important contributions that could have been made upon the subject of glaciers, and there is equally little doubt that the discovery constitutes one of the most painful incidents in the history of science. It is to the credit of Agassiz that he left the fitness of Forbes's action to the judgment of history, taking little part in the bitter discussions that soon grew out of it. Among Forbes's own countrymen there were many, however, who saw in it one of the manifestations of that spirit of greed which, to the credit of science, has rarely profaned its temple;* and after forty years, when both the men have passed away, this controversy still finds a place in literature.†

Forbes's publication of his results obtained on the Mer de Glace showed naturalists that they were dealing with phenomena of movement which indicated a close

* In his annual lectures on glaciers before his students he never made a reference to this unhappy event. He would discuss the facts concerning the motion of glaciers, giving Forbes full credit for his masterly work, without a word that could imply the sense of wrong under which he justly labored.

† In a recent work, designed to defend the memory of J. D. Forbes, his son, Professor Forbes, gives us a *pièce justificative* from Mr. John Ruskin, than whom no man could have a more eloquent defender. This is so remarkable a piece of pleading that it deserves the little additional publicity that its reproduction here will secure for it. It is extracted from Letter Thirty-four of "Fors Clavigera," published first in 1873.

"But fancy the feelings of poor Agassiz in his Hôtel des Neuchâtelois! To have had the thing under his nose for ten years, and missed it! There is nothing in the annals of scientific mischance (perhaps the truer word would be scientific dulness) to match it; certainly it would be difficult for provocation to be more bitter, — at least, for a man who thinks, as most of our foolish modern scientific men do think, that there is no good in knowing anything for its own sake, but only in being the first to find it out. Nor am I prepared altogether to justify Forbes in his method of proceeding, except on the terms of battle which men of science

general resemblance between a glacier and that of a river. The subsequent publications of Agassiz also affirmed the fact. They both have a more rapid movement in the centre; they both increase their flow in the steeper parts; they both flow more swiftly when they are crowded into a smaller channel. The subsequent researches of Forbes, which were made with a skill and labor which we cannot too much admire, established all these points beyond question.

Coincident with Agassiz and Forbes, another acute observer came to the same conclusion concerning the movements of glaciers. M. le Chanoïne Rendu, who had long and intelligently studied the face of glaciers, published in 1840, some time before Forbes's results were obtained, a treatise entitled "Théorie des Glaciers de la Savoie," which for its perspicuity and independence of thought cannot be too much admired. In this he calls attention to the fact that the central part of the stream of ice moves more rapidly than the sides, though it is possible he based this conclusion on incorrect conceptions of certain facts. Unfortunately this publication was obscurely made, and the conclusions of M. Rendu exercised no immediate influence on science.

Resting on his observations, Professor Forbes proceeded to give a theory concerning glacial motion, which, though it has failed to command final confidence, certainly constituted a definite advance upon the hypotheses that had gone before it. Possessed by the resemblance between the movement of a river and a glacier, Forbes's hypothesis supposes that a mass of ice is essentially a viscous body, each particle moving over the other in its flow, as the particles of water move in their streams, only requiring a far greater pressure to affect their motion. He illustrates his conception of glacial movement by frequent reference to other substances, the viscosity of which we recognize in ordinary experience, such as tar,

have laid down for themselves. Here is a man has been ten years at his diggings; has trenched here, and bored there, and been over all the ground again and again, except just where the nugget is. He asks one to dinner, and one has an eye for the run of a stream; one does a little bit of pickaxing in the afternoon on one's own account, and walks off with his nugget. It is hard. Still, in strictness, it is perfectly fair. The new-comer, spade on shoulder, does not understand, when he accepts the invitation to dinner, that he must not dig, or must give all he gets to his host. The luck is his, and the old pitsman may very excusably growl and swear at him a little; but has no real right to quarrel with him, still less to say that his nugget is copper, and try to make everybody else think so too."

The friends of justice can well afford to leave this act of Forbes exactly as it is here placed by his ablest defender. Agassiz had found the one rich "placer" of the Alps; he invited his friend to see his ground, and his friend, being a more skilful miner, knowing better where to seek the rich nuggets than his host, availed himself of a spare hour to carry away the best the workings afforded. We can only thank the scales of fortune that they show such gold to be dross in the hands of its possessor.

or wax, or molasses (treacle, as the British call it). We regard the movement of a glacier as essentially of the same molecular sort, that is, every particle sliding over every other in the movement. In the hands of his followers this theory has sometimes assumed a somewhat different shape, so as to exclude certain criticisms; it is then made to mean that the ultimate tangible elements of the glacier, the bits of ice into which it is divided, slide over each other, as, for instance, a heap of peas when poured on a sloping surface, or, as Mr. Ruskin suggests, a mass of fresh herrings with their slippery bodies; but Mr. Forbes's hypothesis did not conceive this form of viscosity.

No other hypothesis of glacial motion has proved so captivating to many minds as this. At first the evident objection that ice was not viscous in the form we ordinarily know it, that it is the most brittle of substances, obstinately refusing to be stretched in the slightest degree, had no sort of influence upon his followers. Paradoxes are pleasant things to many minds. Science so often goes counter to ancient prejudices that apparent incredibility is often taken as presumptive evidence. Relying upon the fact that the forces of the glacier are gigantic in their power, and upon the fact that ice when squeezed can be made to take any form, they held intently to this theory, which, indeed, for a time possessed the field.

Gradually, however, a sense of the essential incompleteness of this hypothesis began to possess the minds of inquirers. Although a molecular movement might account for parts of the phenomena, it could not explain the most perplexing of the difficulties that beset the path of the unprejudiced student.

The next considerable suggestion was that of Professor John Tyndall, who, calling our attention to an almost forgotten experiment of Faraday, proceeded to show how this might explain some of the facts that stood in the way of Forbes's hypothesis, and account for the motion of glaciers.

The property of ice to which he called attention is one that can be illustrated by a very simple experiment. If two pieces of ice are pressed against each other, they adhere together. It is this which enables the snow of a snow-ball to unite in a close-knit mass, and it is doubtless to this, as Tyndall here shows, that we owe the soldering together of the ice after it has been dissevered in the séracs of a glacier. But Mr. Tyndall extended his hypothesis much further. He suggested that the movement of a glacier might be exemplified by a succession of fractures and regelations of the mass, a slight movement of the ice taking place with each fracture, the adjacent ice faces again cohering after the movement had satisfied the strain, and so by

innumerable rivings and resolderings the ice moved onward in its descent. There can be no doubt that this hypothesis is competent to explain a part of the facts involved in the movement of a glacier, but we are as yet without any proof that innumerable fissures, such as this hypothesis requires, are formed in the mass of a glacier. All the facts we have in hand point to a far more intimate and detailed movement of the ice than can be allowed in this hypothesis. So, although it cannot be said to have been overthrown, it does not at present command by any means a general assent.

Mr. James Croll, to whom we owe so much else concerning the physics of glaciers, has also presented us with a remarkable hypothesis concerning the cause and nature of their movement. This hypothesis is, as might be supposed, very original in its suggestions. At the outset of his propositions, Mr. Croll calls attention to the fact that ice is transparent to heat. If we place a sheet of ice in an opening in a cell from which all access of light and heat is excluded save what comes through the ice, we shall find that the rays of heat pass through it, not so rapidly as the rays of light, still with a certain power. In other words, a degree of heat sufficient to melt the ice may pass through it without overcoming its frozen state. Mr. Croll then shows that the only way in which this heat can pass through ice is by the successive melting of the molecules of ice it encounters on its way; each molecule, as it is melted, parting with its heat to its neighbor on the inward side of the ice, and returning to the solid state, shortly to be remelted by the heat transmitted by its outer neighbor. In this way alone can we, on the accepted explanation concerning the nature of heat, account for the diathermancy of ice.

Mr. Croll then proceeds to show that glaciers must be penetrated in every direction by rays of heat, which affect the momentary melting of every particle of ice as they pass, and that this movement is undergone with great rapidity in short spaces of time by every particle of the mass. While these molecules of water are for the moment fluid, they are free to obey the impulse of gravitation, and will fall a little way into any cavities that exist in the ice, refreezing as soon as the heat passes on. An infinite number of these slight movements will be integrated together into a distinct motion of the glacier in the direction of its slope.

This hypothesis shows the skill of its author in leading us to conclusions from accepted data which have been unforeseen until perceived by his acute mind. Yet we cannot admit that it accounts for many of the features of glacial movement. It will, for instance, apparently not account for the movement of glaciers

in the long Arctic night. Yet we must believe that their motion is continued at such times. It will not account for the greater speed of glaciers in proportion as the slope increases, or for the increase in the rate of movement when the ice is crowded together in a constriction of the valley. So, although the cause he supposes to act may be a true cause, it cannot be considered as explaining, by itself alone, the movement of the ice.

Yet another theory is now finding favor with some naturalists. Mr. James Thompson, a physicist, to whose labors we owe much, called attention to certain peculiar properties of ice when submitted to pressure. Owing to the fact that it expands in cooling, ice differs from other solids in that it, on increase of pressure, lowers its melting-point. This conclusion, arrived at by theoretical considerations, is abundantly substantiated by experiment. We may liquefy ice by means of pressure, or we may more easily do what amounts to the same thing, prevent it from freezing by pressure derived from its own expansion. An old experiment is to seal water along with a shot, in a gun-barrel, and then expose it to a very low temperature. Even at zero of Fahrenheit the rattling of the shot when the barrel is moved will attest the molten state of the imprisoned water. Now, if water may be melted by pressure, may it not be that the pressures in a glacier are sufficient to effect its liquefaction? Thompson's calculations show that each atmosphere of pressure lowers the melting-point of ice by .0025 of a degree Fahrenheit. Assuming that the temperature of the mass of a glacier was as low as 30° Fahrenheit, it would require a depth of ice equal to twenty-eight thousand feet to effect the melting of the ice by pressure alone; but a great deal of the glacial ice must be of a temperature very little below the freezing-point, so that in many cases the pressure necessary for melting really would be brought about by a few hundred, or at the most a few thousand feet of thickness. There can be no doubt that the ice in the lower part of a glacier of the Swiss type is much nearer the melting-point than the higher parts of the glacier, and in this way we may have a constant tendency of the ice to pass into a molten state that may not be without effect, even in relatively thin ice.

We cannot suppose that much effect in liquefying the ice is exercised upon the greater part of an ordinary glacier by the pressure, yet this pressure may act in a somewhat modified form and in a local way through the strains that are constantly penetrating every part of the ice. This may be readily conceived if we look upon a glacier as a mass of ice in which the pressure at any point is constantly varying from

the accumulation and release of strains generated in the movement. A pressure of many thousand tons may at one moment be brought upon a very small mass of ice, and in the next, by some small readjustment of the glacier, transferred to some other point. If the ice is near the temperature of melting, as in most cases it must be in the lower parts of a glacier, this constant changing of the strain will bring about the momentary melting of certain points in the ice. When these particles of water are liquid, they will be free for an instant to fall in any direction in which they may be impelled by gravity or pressure. If a fissure plane penetrates them, they will be drawn into it just so far as is necessary to ease the pressure to the point where the water may freeze. The pressure under which this water moves will produce friction, and this friction will be converted into heat, which will enable the water to keep melted a little longer than it otherwise would. In its movement this water melted by pressure will frequently encounter the ordinary water which at 32° is pouring through the interstices of the glacier. When it encounters such water, the chances are that it will not all again freeze, but will become a part of the water that penetrates the ice, and finally escapes in the subglacial streams. This action may account for the singularly rapid motion which comes over the lower parts of a glacier during the latter days of the summer, when the mass of ice slips forward much more rapidly than it can be replenished from above, and so is drawn out like a telescope, lowering the surface as it pushes forward to the region of more rapid melting. This collapse of a glacier can, it seems to me, be, in part at least, explained by supposing, as we may fairly do, that the ice in this lowermost section is very near the melting-point, and that the strains are constantly reducing parts of the ice to the state of fluidity, and so the movement takes place more rapidly than in higher and colder regions. This hypothesis evidently cannot account for all the motion of glaciers; it must be essentially without effect in the upper parts of the ice, where the temperature is much below the freezing-point. In the névé especially it cannot be of much avail. Yet even there it doubtless aids in compacting the snow and converting it into solid ice. In the summer season the snow warms the névé to a certain depth, in part through the conductivity of the mass, and in larger share through the penetration of the molten water through its porous structure. When the mass is brought to near the melting-point, even the slight pressure of a few feet of materials will suffice to bring about the phenomenon of regelation, which depends upon the effect of pressure in melting the adjacent faces of the snow crystals, or the rounded globules into which they are transformed after a little exposure to the sun. The fact that

pressure melting occurs even in the upper regions of the névé, where the snow is raised to near the melting-point, though the strains there are comparatively slight, shows us that it may occur in the lower regions of the ice, where the same conditions of temperature obtain.

We could add to these hypotheses one or two other suggestions of lesser value, such as that of Mr. William Hopkins, who advanced the theory that the ice moved by pure sliding, each large fragment moving by its own proper slipping, until it became wedged with its neighbors. In a word, this theory supposes that the ice must be divided into a number of long strips, each of which crept by itself down the stream. This suggestion is in conflict with all we know of glacial movement. Forbes has distinctly shown that the most compact sheets of ice move at different rates in their different parts without any fissures between the several parts.

To sum up our knowledge of glacial movements, we may set before us the following propositions: —

Every part of a glacial system is in gradual movement with a speed that, other things being equal, increases in rapidity from the uppermost snow fields to the point where the ice finally disappears. This movement extends to the snow just after falling, and before it has time for much compacting. The snow that falls on our New England hillsides in winter, and accumulates in the pine forests to the depth of several feet, slips down their slopes in the manner of a glacier. To give one of many instances, we may take the remarkable example of a destructive movement of snow that occurred at Augusta, Me. The facts, which were brought to my attention by my colleague, Mr. C. E. Hamlin, of the Museum of Comparative Zoölogy, are as follows: The cemetery of Augusta is situated on a hillside which is terraced to make places for graves. On this terrace snow accumulated one winter so as to fill up the re-entrant angle it formed with the hillside. When in the spring this snow melted away, it was found that the upright tombstones and the iron fence that surrounded the graves were broken off near the surface of the ground, and moved in the direction of the general slope of the hill. The following account which has been kindly furnished me by Mr. Hamlin gives all the details of this interesting accident:

"At the close of the winter of 1853–54, there occurred in Augusta, Me., an incident of interest as respects its geological relations. The old Augusta cemetery is situated upon the upper half of the long eastward slope of a height that rises on the west side of the town, known in the early days of the place as Burnt Hill, now as Mount Pleasant. The lower part of the original burying-ground has a nearly uniform inclination of seven degrees to the east, but the

upper half has a steeper pitch of about eleven degrees. Above the west line of the ground the hill was too steep to be readily available for use, and this circumstance probably determined the former limit of the cemetery in that direction.

"In 1836 several citizens bought from the owner of the higher land a strip of ground adjacent to the west line, running north and south, and wide enough for a single row of family burial-lots. The lots were formed by digging into the hillside, and when finished constituted a terrace, *A D*, thirty-three feet in width. The necessary grading made, of course, part of the slope, *D E F*, steeper than at first.

"In the course of years these lots were occupied by graves, marked by upright slabs of white marble. Several of the lots were enclosed with iron fences. Fences and slabs remained undisturbed till the severe winter of 1853–54, when snow fell to an unusual depth, and a great quantity was blown over the brow of the hill, and lodged upon the terrace just described. The snow accumulated most on the more northern lots of the row, since above them the upper portion of the hill rose steepest.

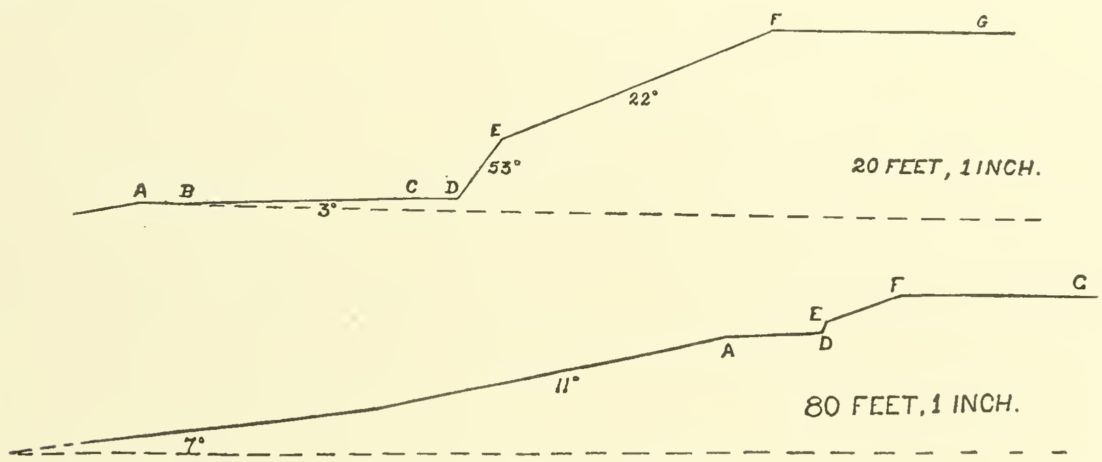


FIG. 21.

SECTIONS OF TERRACED SLOPE, AUGUSTA, ME.

"In May, 1854, I chanced to visit Augusta, and in one of my walks observed that the gravestones on two or more of the northern lots were all, without exception, snapped off square at the surface of the ground, and prostrated eastward, that is, in the direction of the hill-slope. The castings of two fences were more or less broken and pushed to the east. Suspecting from appearances the cause of damage, I sought the superintendent of the cemetery, and was by him informed that the 'settling' of the snow, as he expressed it, had, on the approach of spring, broken the slabs and castings in the manner I had noticed. The fact was, that the snow mass, which had lodged in the angle, *A D E F*, formed by the hillside and the nearly level terrace, had, while thawing, not only settled vertically downward, but had pushed forward or away from the earth bank, *D E*, behind it, with power sufficient to produce the results enumerated. Here, then, had been what, but for the absence of ice, might be termed a *transient glacier;* and the broken stone and iron bore testimony both to the force that was exerted, and the direction in which it acted.

"The owner of the two or three lots on which the greatest injury was done, removed the remains of their friends to another cemetery, and the lots thus vacated have never since been

occupied. But in the cases where the damage was less, repairs were made; and as for the last twenty-six years no similar mishap has taken place, it is evident that the same conditions, in the same degree at least, have not been there repeated. I have, however, learned from a late superintendent, that in the steepest parts of the newer Forest Grove Cemetery, which lies a little south from the old one, on the east slope of the same hill, a few slabs have been broken by the pressure of snow.

"The instance above stated explains clearly certain effects that I have more recently observed in several localities, but on the largest scale upon the flanks of Mount Katahdin, and which are to my mind otherwise inexplicable. The most striking of these effects I shall describe in a paper, now in course of preparation, upon the physical geography and geology of that mountain and its vicinity."

As before remarked, the steep hillsides in snow-clad countries show the same action in a less distinct way. Ascending any of our forest-clad mountain slopes of steep declivity, we find the rubbish that covers them heaped up against the upper side of the tree-trunks, as if a strong stream of water had flowed down the slope. This is doubtless caused by the downward sliding of the snow. I am inclined to believe that this action is not without effect upon our mountains. Very little if any direct wearing of the rock results from it, but the bed of vegetable mould is, by these creeping sheets of snow, constantly being urged down the slope, and in this way the summits are deprived of the protecting earth mantle, and become more exposed to the action of rain and frost. It does not seem too much to say that our mountain sides are, for a part of each year, the seats of glacial action precisely like, though very inferior in power, to that which acts in the névé region of an ordinary glacier. The duration of this action is brief; it is limited to the periods when the snow is somewhat compacted by melting, and the actual movement in any year is perhaps not more than a few inches or a foot at most: but the aggregate effect in moving the decaying vegetable matter downward is worthy of more careful study than the writer has been able to give it. We can only bespeak for it the consideration of those who are better placed for the detailed study of the phenomenon. A few stakes placed in the winter's snow upon our mountain-sides, and carefully aligned with permanent marks, would soon show the real extent of the movement.

Next we notice that a glacial sheet moves more rapidly in the centre than upon the sides, more rapidly at the top than at the bottom, and more rapidly when it is compelled by the accidents of its walls to pass through a narrow channel than when it is permitted to expand in every direction. These facts show us that the movement

of the ice extends to all its parts. It seems certain that if we could put into the glacier at its head a thousand colored ice cubes an inch in diameter, and gather them at the foot of the stream, we should find every one of them greatly distorted by the movement, even if we could secure them from being fractured in the crevasses of the glacier. It is likely that the movement affects even smaller masses of the ice, and that cubes of one tenth of an inch, or even one hundredth, would share the same fate.

It is probable that a good deal of the melting of the ice takes place from the friction of the mass on its bed and on itself. The amount of this melting is about equal to the heat which would be required to lift the ice up to its point of starting. This is a small element in the glacial wear, but it is worth consideration, as it adds to the sum of the forces that effect the motion.

In considering the motion of glaciers, we shall have for the moment to limit ourselves to the glaciers of Switzerland alone; for, as we shall see, the problem with which we have to deal when we come to the task of explaining continental glaciers is of quite a different nature.

The important hypotheses that have been advanced to explain the motion of the local or Swiss type of glaciers are as follows; the reader will find the description of the hypotheses in one column and the objections to it in a parallel column of the text:—

Expansion of Freezing Water.	Objections.
Charpentier and Agassiz believed that the expansion of the water which penetrates the fissures of the ice during the freezing that comes at night or in the winter drives the ice down towards the end of the glacier.	This expansion cannot be enough to urge the ice onward, and if the force were considerable the result would be simply the expansion of the ice upward, that being the easiest way for it to move. Moreover, the cold of the nights penetrates but a little way into the ice. A true cause, but slight in power.
Modification of the Foregoing Theory.	
The fluid water of the glacier exercises a powerful hydrostatic pressure on the ice, and so aids gravity in carrying it downward.	This is a true cause. The water in the crevices would act to help gravity, for it is freer to move than the ice, and is not held back by the friction upon the bottom and sides of the glacier that diminishes the effectiveness of gravity on the ice. But it cannot act in the névé regions, nor in the very compact ice that shows very few crevices.

Viscosity.

Forbes supposed that ice is a viscous substance, and creeps down by the movement of each particle of ice on its neighbor, as in a mass of tar or treacle.

Objections.

Ice is not a viscous body; the strains in the névé region are not great enough to cause it to act as such a body does. The known rigidity of ice is such that the strains are in these glaciers insufficient to explain the movement on this hypothesis. There is no acceleration of velocity such as would occur on a steep slope if the ice were viscous. This theory doubtless presents the facts of glacial motion in a good shape, but it is based on an undemonstrated assumption of the qualities of ice.

Regelation.

This supposes that the ice is divided by fissures into very small fragments, each of which falls a certain distance by gravity, and then again solders itself to the mass.

This would account for the rebuilding of the glacial mass after the sundering that takes place in the séracs, but we have no evidence that the ice is ever fissured in the manner supposed by this theory. Moreover, it cannot account for the movement of the soft névé, which evidently is not fissured in any way that would admit this explanation. A true cause, but of itself insufficient.

Diathermancy.

This theory of Croll supposes that the passage through the ice of heat derived from the sun or the earth melts each particle in succession, making it free to fall a little way before it freezes by parting with its heat to its neighbors, and that these minute movements are integrated into a general movement of the glacier.

This theory is unhappily based upon another theory. We do not *know* that the process of passage of heat through ice is anything like that required by it. Moreover, according to it, thin ice sheets should generally move faster than thick, and the slope of surfaces should have little to do with their rate of motion. The opposite is the case. Furthermore, the ice during the polar night should generally cease its motion. The only heat that it can then be receiving is from the earth, and this is relatively very small in quantity. The névé during the winter, where never in a temperature above the melting-point of water, should not move at all, yet it certainly does move. This theory, possibly a true cause, must be regarded as of less value than the others that have been mentioned.

Pressure Melting.

This hypothesis rests upon the fact that the ice has its melting-point lowered .0025 of a degree Fahrenheit for every atmosphere of pressure, and that the weight of the ice or the strains acting in

We have seen that if the ice was at a degree cooler than 32° Fahrenheit, the thickness of the glacier would have to be equal to fourteen thousand feet to produce pressure melting. As the Swiss gla-

the glacier produce this pressure; that in the moment between the liquefaction and the escape of the water to a pressure so diminished as to allow it to freeze, it may fall in the direction of gravity.

ciers never approach this thickness, melting from this cause could not take place, save when the temperature was very near the melting-point. This approach to the melting-point takes place frequently on the surface of the nevé; near its base the ice is generally too much below the freezing-point to make this cause of value. But in the section near the end of the glacier the ice stream, especially in the summer season, acquires greater warmth, and is then for a considerable part of its course nearly at 32° Fahrenheit. Then the pressure resulting from the weight of the glacier on its base becomes again operative, and the rapid collapse of this part of the glacier may be due to this cause. In other words, it is probably a true cause, but is incompetent to explain all the phenomena of glacial movement.

We have indicated, in the foregoing tabulated statement of the theories of glacial motion and the objections thereto, the general conclusion to which we find ourselves forced. This is, in effect, that many causes co-operate to effect the movement of such ice masses, and that no one of these probably ever acts alone in the work of moving a great glacier from its source to its end. It is likely that the different parts of the ice stream are more or less under the influence of all the forces suggested by these several theories. In the unconstrained névé, that practically does not feel the friction of its boundary walls, the most of the motion must be by the slipping of molecule on molecule,—a motion not due to viscosity, but taking place in much the fashion suggested by Forbes's hypothesis. In the névé the diathermous theory of Croll may perhaps also prove an aid to our understanding; while pressure melting probably acts whenever and so far as the summer sun lifts the temperature of the ice. In the region of the séracs regelation helps us to understand the motion of the glacier. The ice, broken into bits by the strain to which it is subjected, is soldered together by the action of this peculiar law. As pressure melting is the cause of this recementation, it also operates here. When the glacier enters upon its path between the bordering walls of the mountain valley, we have to call in all the possible causes of motion to account for its advance. The thrust from behind compelling the particles to slip on each other in the fashion supposed by Forbes may now come into play. Regelation still acts to heal every wound, and pressure melting operates as soon as the relation of the strains to temperature permits. It is probably in this

way that the ice creeps down from its source to the point where the heat releases it from the long struggle, and permits it to rush on freely to its goal, the sea.

We claimed for the theory which we were compelled to frame to account for the occurrence of glacial periods the peculiar merit that by bringing many causes to bear upon the explanation of the facts we came nearer to the course of nature than we are likely to do by a hypothesis which rests upon a single cause. The same advantage may be asserted concerning this view of the forces that effect glacial motion. So far the students of glacial motion have generally been in the position of advocates maintaining the sufficiency of some single train of causation to explain effects that are from their nature likely to be composite in origin. It is not necessary to call the attention of the considerate student of natural phenomena to the complexity of causes in the machinery of the earth's surface. All his experience tends to show him that every inconsiderable event is the result of varied and generally complicated forces. The winds that blow, the rivers that move in their courses, the streams of the sea, all are the products of complicated causation, and no one force will explain their varied nature. So we might, from an *a priori* point of view, expect that glaciers would move in obedience to various co-operating causes.

The movement of local glaciers may aid us in our efforts to understand the much more obscure problems of continental ice masses. In glaciers of the Swiss type we are always in a position to use gravitation as the *primum mobile*, all the other causes being only secondary agents that operate to help the work of gravitation and enable the rigid substance to flow. From its summit to its base there is a continuous descent, or if there be depressions the thickness of the ice over them is so great that they are not to be considered as obstructions. Even in the lowest part of a Swiss glacier the ice has an average declivity of several degrees, and the gravitative power urging the ice down the slope is very great.

When we come to consider the continental type of glaciers we have to leave gravity, as it works in Swiss glaciers, almost out of account. Taking the existing slope of the lands, no possible hypothesis will enable us to see how gravitation would then exercise any force that would affect a glacier of the ordinary type.

From the base of the Laurentian Hills to Southern Ohio is, in the present altitude of the land, a descent of about one thousand feet. From the St. Lawrence to the shore of Connecticut the descent is not over one hundred feet, or not more than the bed of the most gently flowing river. If we accept the conclusion that

the lands were sunken during the glacial time in their northern parts, whether we believe the depression to have been due either to the change in the altitude of the sea or to a positive down-bearing of the land areas, we shall find even these slight slopes destroyed or replaced by others inclining toward the polar regions. The proof of this subsidence appears to be irrefragable, but we will consider the lands to have been all the while in their present position. Even then the difficulties of effecting the motion of glaciers by the action of gravity is wellnigh insuperable.

The only way in which gravitation could be brought to act under these circumstances would be by the heaping up of the ice in the northern regions to so great a height that the slope of the upper surface to the south would be as great as that which suffices to impel ordinary glaciers down their declivities. If this could be supposed, then gravitation might drag the ice over its bed. If we could imagine the ice to have been indefinitely thick in its northern parts, it would even cause a movement of the ice up the slope which the depressed surface of the lands doubtless then offered to the ice. But the thickness of ice that even the least of these suppositions requires is too great for acceptance; to give a slope of over one degree from the shores of Hudson's Bay to New York would require a thickness of many miles at the source of the stream: it is not necessary for us to accept this supposition. We must first see whether the southward movement of the ice which the scratches and transportation of débris indicate is not reconcilable on some other basis than that to which we are led by the phenomena of ordinary glaciers.

In the résumé of causes competent to account for ordinary glaciers we have seen that there are several which can contribute and probably do work together to effect their motion; which of them can we suppose to have been operative in effecting the motion of continental glaciers? Manifestly the most effective of them will be those which require the least aid from gravitation. Regelation, or the flow effected by the slipping of fragment on fragment, is manifestly unlikely to have had any great share in the movement of an ice sheet that lay as a great plain wrapping the continental hills and valleys beneath its wide expanse.

It is to pressure melting and the incessant underrunning glacial streams that we must look for the principal activity of continental glaciers. Let us examine the evidence to see how far we can explain the glacial record through these limited forces working to effect the motion of continental glaciers over great distances of little or no declivity. To do this we must take a somewhat more critical view

of the evidence than we have yet done. This evidence may be grouped in the following propositions: From the ice front of the continental glaciers northward to the Arctic Circle we have a continuous series of scratches which show a general direction in the movement of the ice from the north to the south. There is a certain variability in this movement, which may be well seen from the following tables of direction of the ice in different regions of North America:* —

N. of Gulf of St. Lawrence	S.E., S., S.W.	E. New York	S.
Quebec, Canada	S.W.	W. New York	S.S.W., S.W.
Ontario, "	S.W.	Ohio	S.S.W., S.W.
N. of Lake Superior	S.W.	Michigan	S.S.W.
Lake Winnipeg	S.W.	Wisconsin	S.S.W.
Nova Scotia	S.E.	Indiana	S.
Maine	S.S.E.	Illinois	S.
Massachusetts	S.S.E., S.	Upper Missouri River	S., S.W.

From this assemblage of facts we may make sure that the general trend of the glacial movement was from north to south, but that the local variations of direction were great.

The next fact in the order of importance is the distance to which materials were transported overland during the ice time. On this point we have less accurate information. The following list will give a few tolerably well-ascertained facts that probably represent the maximum carrying power of continental glaciers: —

Maine, 130 miles.
New Hampshire, 90 miles.
From the Laurentian Hills to Cincinnati, at least 500 miles.
Wisconsin, 300 miles.
From the Central Alps to the Jura, 80 miles.

The transporting action of continental ice should not be confounded with the carriage of stones by icebergs. Iceberg carriage doubtless conveys drift matter for much greater distances.

The last point is the energy with which the ice was pushed along in its southern course, and the deflections that obstacles exercised upon it. The vigor of the advance is proved to us by the greater wearing it brought to bear upon the upstream side of steep mountains. This has affected their slopes to a considerable degree, wearing down their northward slopes to much more gentle declivities than they show upon the south. Yet it is possible that this effect has been exagger-

* The most recent map of the direction of glacial striæ in North America may be found in the Geology of New Hampshire, Vol. III. p. 323, and is here copied with Plate XX.

ated, as many of the cases of crag and tail in New England prove, on examination, to consist largely of drift.

Instances of this sort are abundant in the valley of the Pemigewasset and its tributaries. These were, doubtless, formed in the closing periods of glacial time, when the shrunken ice was unable to move great masses of detritus. The ice, having a weakened scouring power, tended to heap the waste into pockets, building inclines

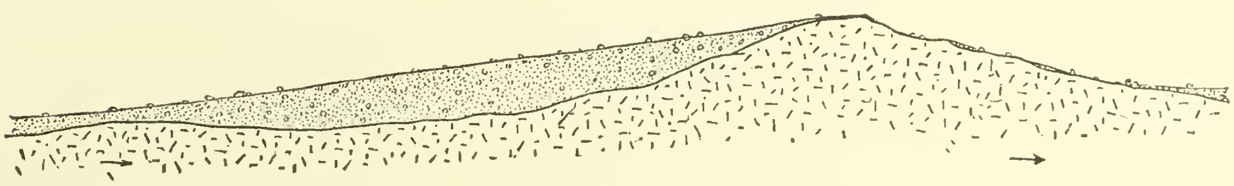


Fig. 22.

Drift Slope against a Rock Hill, reversing the usual Form of Crag and Tail.

on the northern faces of the steep hills, or filling the lake basins that the deeper ice had excavated. Yet there can be no doubt that during the most extended state of the ice sheet it pushed against the northern faces of these hills in a way that shows that it was urged on its course with very great power. The power of the ice to override obstacles that tended to turn it aside is also clear. Even a great mountain mass, like the White and Franconia Mountains of New Hampshire, turned the course of the base very little.

As a whole, the movement of the ice was singularly uninfluenced by the surface over which it flowed. This is best seen in the case of valleys whose general trend is with the glacial current, but which depart from it in their greater windings. In such positions, if anywhere, we should expect the stream of ice to have been turned from its free course, and made to conform to the general trend of the surface. In the case represented by Fig. 10 (page 45), of the same nature as many others which could be adduced, the ice found it easier to climb the boundary hills than to twist itself into conformity with the general trend of the valley.

We see that a local glacier would have found no difficulty in making its way in such cases. The curves are no greater than those followed by existing ice streams, as shown in Plate IX.; we are therefore forced to the conviction that the mass of ice above this valley must have been great enough to drag the part

in the valley onward in the direct path. In the very bottom of an oblique valley the ice appears to have been somewhat deflected, but as soon as we rise a few hundred feet above the floor we have evidence that the stream of ice obeyed the general motion of the ice sheet. Slight departures from the general line of motion may be seen on almost any irregular rock surface that bears glacial scratches. But these deflections are very local. All the great valleys, such as the Hudson, and even the narrow gorges of the mountain districts, show that the ice was not readily diverted from its path.

All writers who have hitherto considered the question of continental glaciers have assumed that the ice sheet moved continuously southward until it traversed the long lines marked by the scratches from the centre of dispersion to the southern line of the sheet; and at first sight this is the most reasonable interpretation of the facts, but it is doubtful if the evidence warrants this conclusion. The following hypothesis will bring before the reader another and apparently simpler explanation of the way in which this record could have been made: —

Let us suppose, as we are justified in doing, that the last ice time came on in a somewhat gradual manner; the ice sheets extending southward, year by year, until the areas covered by the ice at its culmination were attained. The movement of the ice from a score of miles back of its southern border would have been easy, and along this front there would have been a constant shoving southward of the detritus in the grasp of the advancing front of the ice. The inner regions of the glacier, lying enclosed by the mass of ice about them, would have moved with less freedom the farther we pass from the ice front. Here the ice would accumulate to great thickness. We have seen that the ice was certainly over a mile deep at Mount Washington; and as in Greenland the slope extends from the shoreward regions steadily to the interior, so we may believe that a similar increase in depth would have extended into the interior of the continent. In these enclosed areas we may believe that the ice, restrained in its outflow by friction, would accumulate to a great depth, perhaps sufficient to produce pressure melting. Our doubt on this point lies in the impossibility of finding any basis for determining the temperature of the ice during the glacial period. The great depth of the ice sheet, even allowing, as we must, for the submersion of the lands, which would, as far as it went, tend to diminish the effect of this depth, would have brought its surface into the higher and colder regions of the atmosphere. Yet, to have the great snowfall that is clearly proven to have occurred in the glacial period, we could not have

had an extreme cold in this region covered by continental glaciers. Moreover, a certain amount of heat would have been derived from friction and from the interior of the earth. In Switzerland this does not prove to be very efficient; but the friction in continental glaciers was probably greater, and their slower movement would give more time for the internal heat of the earth to do its work of elevating the temperature of the ice. If the temperature of the ice was anywhere near the freezing-point of water, then the accumulation of ice to the thickness that we had at the White Mountains of New Hampshire would certainly bring about pressure melting at the bottom of the glacier; and even a less thickness would, with the changing of strains, effect this result at one point after another.

We can readily see that this pressure melting might greatly aid our conceptions of the movement of continental glaciers. Under the pressure of the overlying ice the parts of the glacier most deeply buried would, from time to time, be crushed into water. This water, inasmuch as its liquidity was due to pressure, would only be free to move until it attained a point where the pressure would be sufficiently diminished to permit its return to the solid state. In its moment of freedom it would find the line of natural relief either upward through the ice or horizontally along the contact of the ice and the earth. Movement in a vertical direction where there was much pressure melting would become impossible for the reason that, were there any crevices of the ice, they would soon become closed by the penetration of such waters. Furthermore, crevices could not form in ice of this great thickness; the very weight of the ice would crush the walls of any fissures of the ice together, so that it would become a closely welded mass. The result would be that the water molten by pressure would have to move horizontally along the junction of ice and rock, if it is to have any movement at all. It is likely that this movement would be spasmodic in its nature, masses of pressure-melted water accumulating beneath the ice, and gradually rising to the temperature which would permit its remaining molten for considerable distances on its journey. As it from time to time finds a way of escape, it would flow on in a paroxysmal manner, forced along by the pressure of the ice that rested upon it. If such movements existed, they would have a great eroding power. Armed with the harder remains of the worn rocks, urged on by the weight of the ice, they would have a power greater than our mountain torrents under the most favorable conditions. In this way we conceive that the ice of British America may have been carried out, from centre to periphery, in the form of water, and the waste of its grinding borne along by the streams that were formed by the pressure-melted water,

joined to that which was released from the freezing state by the heat escaping from the earth and the heat produced by friction.

The condition of the waste which we find along the old front of the glacier is such as we should expect if water had been a principal agent in its carriage: the fragments are generally of small size and greatly worn; they are rarely scratched, and, though not rounded in the fashion of beach pebbles, are much like the waste that has been subjected to the erosion that takes place in a mountain brook. Moreover, the distribution of the waste is not uniform, as we should expect to find it if it had been carried forward by the regular movement of an ice sheet. It is heaped in ridges and patches, as it would be if its carriage had been due to subglacial streams.

The glacial scratches and the greater wear of the north sides of our hills, which afford the principal evidence of the southward movement of the ice, would be sufficiently explained by our supposition that the border of the ice sheet was free to take on the ordinary motion of a glacier. In its advance southwardly as the ice accumulated, and in its retreat north as the ice disappeared, this front of the ice would sweep over all the lands and have time for the limited work we need attribute to its motion.

This hypothesis rests upon so many assumptions that it would hardly be desirable to present it to the reader, were the difficulties of any other view not very much greater than it presents to us. We cannot expect to find many confirmations of the hypothesis in the phenomena of recent glaciers. Those of the circumpolar regions are the only ice sheets that could throw light upon the conditions of continental glaciation, and these have not received any considerable attention from explorers: it may be that they present insuperable obstacles to inquiry. While the Greenland glaciers resemble those that existed on the continent of North America during the last glacial period, we must not forget the fact that the continental sheet was of far greater area, and also that the subsidence of the northern regions during the glacial period brought about obstacles to the movement of the ice that do not exist in any of the circumpolar ice sheets. None of these can well move over paths of more than three hundred miles in length, while the American continental glacier must have moved over twice, perhaps thrice, this distance in its course towards the sea or the southern lands.

To sum up our little knowledge and abundant ignorance concerning the nature of continental glaciers, we see that their conditions were essentially different from

those of local glaciers; that the same causes cannot co-operate in the same way to explain their movement. We find ourselves in physical difficulties of the most puzzling nature when we try to account for the southward motion of glaciers from the Arctic Circle to the Ohio. Even if the lands were not depressed in the north so as to make it up-hill all the way, the only escape is in assuming that the ice did not move from the far north southwardly as ice, but was driven out in the form of water made molten in part by friction, in part by the heat of the earth, but in larger part by pressure melting. No doubt this hypothesis will be found to raise questions of great difficulty, but it for the moment aids us in our efforts to understand the dynamics of continental glaciers.

CHAPTER XIII.

CERTAIN EFFECTS OF GLACIERS.

Relation of Glaciation to Soils. — Soils of Immediate and Remote Derivation. — Decay of Boulder Clays. — Importance of Glacial Mud. — Origin of Tertiary Sands of Southern States. — Relation of Glacial Action to Gold-bearing Gravels. — Colorado Placers. — Relations of Caverns to Glaciers. — Effect of Glaciers on Coast Lines.

IN the following chapter we shall consider certain effects of glaciers that could not be discussed in the course of the preceding pages without materially interrupting the continuity of exposition to which they were devoted. It has not seemed desirable to trouble the reader with various classes of results concerning the action of glaciers, which are of a very special nature. There are many consequences of glacial work not touched upon in this chapter, which would only be of interest to the special student in particular branches of geological inquiry. These have been omitted as not within the limited province of this work. We shall first consider the action of glaciation on soils. The effect of glacial action on soils is very interesting; and as it has not been noticed in any treatise on glaciation, it will be worth our while to give it attentive consideration.

In regions where glaciers have not acted the formation of soils is brought about by the simple weathering of the rocks. Penetrated by rain-water which is charged with carbonic acid gas through the action of the decaying vegetable mould, the rocks slowly give up their more soluble substances, lose their rock-like nature, and assume the character of subsoils. Into these subsoils the roots of the plants penetrate, and by virtue of their singular expansive force this subsoil is loosened to a considerable depth, becoming thereby mingled with the vegetable matter of the decaying roots and with the mould that is washed down into the cavities these

roots leave when they rot away. Insects burrow into it, and our common earthworms are constantly bringing up its topmost layers to be mingled with the vegetable mould. Gradually a deep stratum becomes confused with vegetable mould, constituting a true soil. Such a soil partakes of the nature of the rock beneath it. If the rock abound in argillaceous matter, the soil will be a clay; if it be a sandstone, it will be sand; if the rock has a large share of phosphates and alkaline matters, the resulting soil will be very fertile.

The extent of the decaying action of surface waters on the soil varies in different countries, according to the constitution of their rocks and the rain-fall. It is less on limestone and slates than upon granitic rocks. In the States of Georgia, North and South Carolina, where the last glacial period did not operate, it is common to find the granitic deposits decayed down to the depth of from fifty to one hundred feet. In New England the decay of the granites has only taken place at a few points on the southern edge of the ice sheet, and is there relatively slight. The ancient decayed rocks were scraped away by the glaciers.

Throughout the non-glaciated regions of the earth the soils are of what we may term immediate derivation, except along the rivers, where they are composed of silt brought by the overflowing waters. There they are a mixture of all the materials that are exposed to erosion by the streams above, and have their fertility determined by the average richness in fertilizing substances in the rocks that eroded to make them.

In the glaciated regions we have a very different set of conditions determining the composition of soils. In place of being derived from the underlying rocks the soil is built upon a mass of débris derived not from below, but from a considerable distance up the course of the glacial stream. On any one acre of soil in the glacial belt the chances are that we have something from every acre of rock for perhaps hundreds of miles away in the direction whence the ice came. This gives these soils a very different character from the immediately derived soils of the non-glaciated regions. We may term them soils of remote derivation.* When the forest vegetation came to repossess these areas, the pines and other conifers, the pioneers of the returning woods, being able to flourish in earth having little vegetable matter in it, soon formed a forest, and began, along with the other plants that accompanied them, to build a soil. No process of decay in the underlying hard rocks was necessary for the making of this soil. Wherever the glacial waste lay, it was good enough

* See Reports of Kentucky Geological Survey by N. S. Shaler, Director, Vol. III. p. 81, New Series.

to afford the basis of a soil, and in a short time a considerable depth of this glacial waste was penetrated with vegetable matter.

This difference in the method of soil-making in regions within and without the glacial belt has given the peculiar characters to the agriculture of the two classes of countries. Glaciated regions are characterized by far more uniform soils than non-glaciated regions. The earth offers there, on the whole, less variety to the husbandman in regions where the ice has acted, but the average of the soil's fertility is perhaps as great as in non-glaciated regions. Moreover, the subsoil has such a nature that it can generally readily be incorporated with the top-soil when desired; this increases its endurance of tillage. On the other hand, the plough is constantly hampered by the erratic boulders that usually abound in all unchanged or little changed glacial deposits. This is the formidable disadvantage of this region. In New England it generally requires at least fifty days of labor to fit any but the soils upon re-arranged drift for the plough.

In the more southern soils the fertility is more irregularly distributed, for it goes with the geological substructure of the district. The soils are a store of the richness derived from the gradual leaching out of a great thickness of rocks, and when they have yielded this store to vegetation they are more completely impoverished than a typical glacial soil. Hence it is that the soils of Virginia are far more worn by the tillage of the last three centuries than those of New England. The less fertile New England fields have profited enough by the decay of their elements, and the working up of their subsoils, to make up for the waste of an agriculture only a little less shiftless than that of the Old Dominion.

This superior endurance of the glaciated soils is especially marked in those elements that are most rapidly exhausted by cropping. The potash, the soda, and the other substances that are least easily restored by tillage, are generally present in the pebbles that make up a large part of their mass, and by their decay, which is facilitated by tillage, yield these substances to the soil. As all agriculture, how ever skilful, tends necessarily to the impoverishment of soils, save perhaps in a few favored spots, it is a matter of congratulation that so large a part of the earth's surface has this enduring quality of soil that the glacial period gives.

The larger part of the glacial soils of Europe and America are in the hands of our own Teutonic race. Very little of the glacial soil exists south of the Potomac, the Ohio, and the Missouri. The prairies are generally beyond its line, and have the qualities of immediate fertility, and are liable to the rapid exhaustion under

bad agriculture that characterizes the fields of the Southern States. Canada is altogether within the glacial belt, and her soils will have the endurance without artificial fertilizers that marks those of Northern England, Scotland, and Scandinavia. Undoubtedly systematic agriculture will do much to arrest the exhaustion that is sure to overtake soils of immediate derivation when carelessly tilled, yet it cannot fail to be advantageous to a country to have in its fields the stubborn yet enduring qualities that are given by the shares of the great ice plough.

The boulder clays formed during the glacial period, and all of the deposits of secondary clays made by the action of water at the close of that time, have a characteristic color that distinguishes them from the clays produced at other times. The absence of organic matter, which, by the acids with which it impregnates the waters of both sea and land, favors the decomposition of detrital materials, caused these clays to be laid down in a very unoxidized state. Generally they are of a bluish hue, and only attain the ordinary yellowish or reddish color of decomposed clays as the waters acidulated by vegetation slowly penetrate into them. The depth to which this penetration of water has accomplished the fuller decay of these clays is a rough yet valuable measure of the length of time that has elapsed since the ice sheet left the country where they lie. In North America this penetration of atmospheric decay is distinctly proportionate to the nearness of the clays to the old glacial front. In Southern Ohio this decay is deep. I know of no boulder clays there that are not darkened to their base, and it is only the very dense brick clays of the terrace deposits along the rivers which were formed during the glacial period that have resisted this change. In Southern New England the decay is less complete. In the parallel of Boston the boulder clay is distinctly changed to the depth of about fifteen feet in the most exposed portions, while the rearranged glacial clays have hardly decayed at all. In Southern New England the change is distinctly less than about Boston. In Scotland, as I am informed by Professor Geikie, Director of the Geological Survey of Scotland, the drift is even less penetrated by decay than in the region about Boston.

This is one more evidence that the retreat of the ice at the close of the glacial period was not as sudden as it is considered by some writers to have been. These differences in the oxidation of the clays must represent a very great lapse of time. It is to the decay of these clays, rather than to any other source of time ratios, that we must look for the evidence as to the length of time since the ice began its retreat.

The erosive action of glaciers aids us in our efforts to understand many sections of the earth's crust that would otherwise prove unintelligible. It is clear that the glaciers tend to give to the sea a far more varied series of sediment than can be conveyed to it by either of the other erosive agents, the rivers and the action of the waves on the shore. Neither of these agents is competent to give to the sea so much coarse waste in the form of pebbles, or so much very finely comminuted sediment in the shape of mud. The amount of very fine mud forced out by glaciers and discharged through their streams is apparent on the least inspection of the water that escapes from beneath them. This mud is much more finely divided than the mud of ordinary rivers. Only great streams, such as the Mississippi, furnish materials in such a completely powdered form, so well fitted for distant carriage by the slow-moving currents of the sea. Not only do glaciers even of the thin and relatively inefficient type presented to us in Switzerland effect many times more erosion than running water would on the same ground, but the larger part of their waste is in a finer state of trituration, and much less oxidized than that discharged by rivers. Data are wanting for a precise estimation of the amount of this free mud in non-glacial rivers compared with that carried by streams that escape from beneath the ice. From some insufficient studies in the matter, I became convinced that in the case of the Grindelwald glaciers and those of the Chamounix district, the amount of mud was some scores, if not hundreds, of times that of the coarse matter that worked out at the end of the glacier. Beneath continental glaciers, where the journey was longer, and, owing to the greater thickness of the ice, the erosive power was greater, the proportion of fine sediment must have been even larger. This sediment would not have remained on the surface of the land, but would have been carried by the water of the glacial streams out to sea, and so would have escaped from the neighborhood of the ice sheet. Much of it was caught in the area formerly occupied by our numerous lakes. We must, therefore, not regard the pebbles and coarse sand that mark the position of the ancient glacier as the principal result of its wearing action; the fine mud that went upon distant journeys to the deep sea was certainly scores of times as great in mass.

In the series of rocks that preserve our only record of the past conditions of the earth's surface we have many sections that show us very great thicknesses of clay slates and shales composed of mud which seem to have accumulated on sea floors that were nearly or quite destitute of life at the time the

beds were laid down. In many cases these shales were intercalated among conglomerates, or in such close relation to them that we may fairly believe that they represent the mud detritus of an ice time. But there are many other cases in which we have the unfossiliferous clays without the evidence of glaciation that conglomerates afford. The Palæozoic period especially abounds in this class of deposits. When we consider, as before suggested, that the conglomerates that afford us record of glaciation could, in the nature of things, only be deposited near the sea-shores, while the free mud that represents the larger part of the erosion of the ice was free to be deposited over a very much wider surface, we may well expect to find many deposits of clay slates and shales that were really produced during glacial times, though there is no boulder bed to show the transporting power of ice with perfect certainty.

Deposited in very cold waters, made up of sediments that contained none of the organic matter that even the purest rivers bring down, perhaps deposited with a rapidity that tended to choke out the life of the sea floors, these glacial muds would be likely to have a lifeless character, proper to so many of our ancient clays.

A good example of this kind of sediment is afforded by the Cambridge slates and other argillaceous elements of the Roxbury conglomerate series in Eastern Massachusetts. Without attaching too much importance to this hypothesis it may fairly lead the student to question whether we may not consider extensive deposits of non-fossiliferous clays in any period as making that level a place where further evidence of glacial action should be sought.

There is another point worthy of note. The free mud brought out by rivers is in a much more completely oxidized state than the mud produced by glacial wear. The river mud is exposed to the acids of vegetation, and generally makes several long pauses in its course to the sea, during which it becomes much decayed. I have never seen this mud form a blue clay when laid down in beds; it always makes a dark-colored mass, showing complete oxidation. Along the banks of the Ohio and other northern tributaries of the Mississippi, there are many deposits of a blue clay, that are apparently to be referred to the time of the glacial period. So far I have failed to find just such deposits of blue clay along the southern tributaries of the Ohio, which did not drain a region covered by the ice sheet. As there seems to be no mechanism of the sea that could convert the gray and yellow clays of our rivers into blue clay, there is an additional reason for suspecting that many clays of the lifeless shales of former periods may be from the glacial streams. In some cases unfossili-

ferous clays may be due to other conditions of deposition; but I know of no other agencies that could cause the color due to their unoxidized condition, and the absence of organic remains.

There is yet another interesting point concerning the erosive action of glaciers, and the effects it has upon the accumulation of ancient deposits. It will be noticed by the geologist, that the southern part of the United States east of the Rocky Mountains is to a great extent composed of detrital materials, pebbly beds, free sand and mud, that have been derived from the waste of the northern regions. The general structure of this great mass shows us clearly that it owes its transportation not to rivers, but to the action of the sea. The method in which this marine transportation has been effected is in itself a problem of much interest. The eastern face of North America has had from the earliest times about its present trend; that is, its general direction has been for many geological periods from northeast to southwest. The winds that roll the sea upon this shore blow at various times from various quarters, but their average direction has been from the north of east. The result is that all the detrital materials that come into the grip of the waves and the shore currents tend to move down the coast toward the southwest. Already a great deal of the waste deposited along this northern shore by the glaciers of the last ice time has found its way much to the south of the line where it was deposited. In the earlier days when the Southern Tertiary deposits had not yet been built, the shore probably inclined much more sharply to the west, and the action of the waves and shore currents would have been much more effective than it is at present.

The only considerable source of sediments along the northern coasts is the waste brought into the sea by the glaciers, or worn from the cliffs of drift which often line the shores. The rivers now bring little detritus to the sea, and there is no reason to suppose that in the past they have carried larger quantities of sand and gravel. In a word, it is most likely that the greater part of the Tertiary sands of the Southern States have been brought to the sea by glaciation, and then transported to their present position by marine waves and currents. Something of the same sort, but on a less extensive scale, may be observed in Europe. There, also, the general trend of the coast is southward, but that trend is interrupted by many irregularities of the shore. I venture, however, to suggest that the great accumulation of sand in the deep angle of the Biscayan Bay gives us a very good specimen of the effect of the trend of shores on the movement of sediments along them. It is quite likely that this accumulation of sand is in part due to the great mass of such ma-

terials cast into the seas to the north of the Bay of Biscay during the last glacial period.

It is interesting to trace the general relation between glacial action and gold-bearing gravels. It often happens that in a country where gold lodes are too small or lean in the precious metals to be worked, or in many cases even to be discerned, glacial action has produced rich auriferous deposits by concentrating the gold which formerly existed in a considerable thickness of rocks into a small mass of gravel. The glacier, in fact, acts to produce the same results as an ore mill. One of the oldest and most effective forms of apparatus for crushing ore is the Chilian arrastra. In it one or more large stones are dragged around a circular trough-shaped track, partly rolling, partly sliding over the ore; a stream of water flows through the ground-up ore, washing away the finely pulverized stone, but leaving the grains of gold in the trough. In many of the mountain valleys of the world the same process is or has been carried on by the glaciers. One of the most interesting exhibitions of this action is shown in the valley of the Upper Arkansas, between the town of Granite and the head of that stream. The following section shows the conditions of this deposit at a point where Twin Lake Creek enters the Arkansas River.

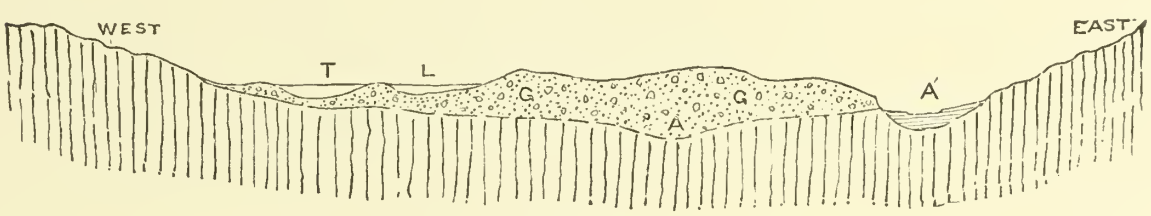


FIG. 23.

SECTION OF THE ARKANSAS VALLEY AT TWIN LAKES.

A, A', old and new channels of the Arkansas River.
G, G, moraine gravels brought into the valley from the west.
T, L, Twin Lakes held in hollows in the drift.

This section is, on many accounts, the most interesting exhibition of glacial action of the local sort that has ever been described. In the region of the continental divide in the west, we have many small gold lodes, all too thin for profitable working. Glacial action has worn away a great thickness of these rocks, and left the heavier part of their waste in the moraine heaps shown in the section. These drift deposits exceed three hundred feet in thickness. They were formed in part within the water of a lake which was caused by a glacial dam, formed by the ice

stream that escaped from the valley of Clear Creek, a few miles below the point where the section is taken. The ends of several glaciers lay in this old lake; the terminus of one of them is still marked by the present basins of the beautiful Twin Lakes. The vast deposit of gravel brought down by these glaciers contains some gold throughout its mass. This gravel has been to a certain extent worked over by the action of the streams since the glacial period, and a second concentration of the gold has been effected in the bed of the Arkansas River, forming a deposit of glacial gravel rich in gold. We may also notice the interesting fact shown in this section that the Arkansas River, after the disappearance of the ice, found its old bed so obstructed by the glacial waste that it was driven to cut a new channel against the side of the cliff, leaving a rim of bed-rock between its present trough and its old bed. This channel is excavated in the rock to the depth of about one hundred feet, with a width of from three to six hundred feet. Its great size is one of the evidences that the glaciers disappeared from this region long before they passed away in New England.

Similar, though less conspicuous, instances of the concentration of gold by glacial action abound in this and other countries. The drift gravels of Ohio and Indiana contain similar concentrations of gold, though not in workable quantities; and on a small scale they are found in New England. The tributaries of Baker's River and the Ammonoosuc in New Hampshire, the dead and sandy rivers of Maine, furnish interesting examples of this action. The glacial sands and gravels of the Rhine are still worked for this metal, and in former days other rivers of Europe furnished gold from detrital deposits, that were derived from ice-worn gravels.

Furthermore we may notice the relation between caverns and glacial erosion, It is a very important fact that no preglacial caverns have ever been discovered. Such cavities in the limestone rocks within the glacial belt must have existed before the last ice period in considerable abundance. It is pretty certain that they would have been filled with the waste of the ice time, yet, as the limestone rocks of northern countries have been extensively quarried, it is not a little singular that they have not yet furnished us with evidence of the life before the glacial period in something like the manner in which they have afforded the remains of the life of the lands since the close of the ice period. If it be a fact that there are no preglacial caverns left in the region occupied by the glacial sheet, we are driven to conclude that the wearing action of the ice during this period extended to such a depth as to destroy the whole of the rock sections that contained caverns. In Ken-

tucky and Tennessee the cavern-bearing section of the earth's crust is not less than five hundred feet thick; that is to say, there are sections five hundred feet deep that are excavated by the caverning waters. It is likely that many other sections could be found south of the glacial belt, of even greater depths, that are full of these underground passages of water. There are many limestone sections in the Alps and other northern regions as likely to be affected by caverning waters as those of Kentucky; if it be true that these sections exhibit no caverns that can be referred to times before the glacial period, it seems that we must accept the conclusion that the erosion of that time removed several hundred feet from the surface of those lands.

New York and New England contain some small caves. All that are known to the writer are the product of erosion that has taken place since the glacial sheet departed from these lands.

The inquiry into this subject is the easier for the reason that the subglacial waters probably did not erode caverns. This work demands the presence of carbonic acid gas in the water, which can only be given in sufficient quantity by the decaying forest bed through which all the ground waters flow. Therefore the line between preglacial and postglacial caverns should be easy to trace. I can heartily recommend the pursuit of this line of inquiry to observers who are well placed for its pursuit.

Reference has been made in the earlier chapters to the action of ice in producing in glaciated countries the irregular topography which along that shore line finds its expression in the singular structures known as fjords. If the reader will take a good map of the Scandinavian coast or of the shore lines of Maine, Scotland, Labrador, or British Columbia, he will see that in place of the rather continuous outline characteristic of most coasts near the equator, he has in these countries a sea border of the most complicated description. A fringe of islands lies off the shore, and the mainland is fretted by deep indentations, that often extend for many miles into the back country. It was long ago remarked that these fjord shores were limited to regions where glaciation may have acted, and though some geologists still doubt the connection between glaciation and this rude fretting of the seaboard lands, this feature in their distribution is presumptive evidence that they are due to glaciation. We may enforce this consideration by a single comparison; the coasts of Scandinavia and of Northern Spain are composed of rocks comparable in hardness, and upon their surfaces the energy of river action is approximately alike, yet in Scandinavia

we have a surface cast into the peculiar topography that where it is cut by the sea gives the fjord zone; while in the Spanish peninsula the shore line has the consolidated type proper to regions beyond the action of glaciation.

Moreover, a close inspection shows us that the contour of the earth's surface that produces the fjords is exactly the same as that which gives us the lakes in the glacial districts; this inspection reveals the fact that many of the indentations which occur along the shores are nothing but lake basins that have had one of their borders made low enough to admit the sea. Wherever we have a chance to study the action of glaciers on the land surfaces, we find that they do just such work as is necessary to make fjords; they carve the rock into valleys and basins, having their greatest length in the direction of the ice flow. Submerge any of the lands that have been beneath the deeper parts of the old glaciers, and they would, when their valleys had been cleared of the waste that cumbers them, exhibit to us the same fjord topography. It is fair to say that, although there are those who doubt the relation of fjords to glaciation, the evidence is altogether in favor of this hypothesis of their origin.

The result of this contour of surface is that all glaciated regions abound in good harbors, and in most cases these island-fringed shores form a safe and continuous shelter for ships of the smaller class, such as mark the beginnings of maritime adventure. To appreciate the value of this feature to the development of man of this region, we should try to bring to mind the extreme obstacles that ordinarily beset the beginnings of maritime life. To men, in their earlier stages of civilization, the sea is the very abode of terror, and even the most maritime people never lose a certain sense of its appalling powers. If a coast be made up of long reaches of unbroken shore, there is absolutely nothing to invite the savage to make the first steps towards navigation, and so whole continents, such as Africa and South America, have developed little of the maritime spirit. If, on the other hand, there is a fringe of islands, such as is afforded by the action of glaciers, these outlying bits of land are constant temptations to the dwellers on the continent. This fringe of sheltered waters is sure to abound in fish, and so the canoes or rafts that would be otherwise limited to rivers are led out to wider waters, and begin the arts of navigation. Such archipelagoes are the natural nurseries of seamen. Men there are in the leading-strings of the sea until they grow up to the strength its dangers demand. Our Aryan ancestors seem to have developed in a region remote from the sea, and to have known little of its arts

until their migrations brought them to the archipelagoes of the Eastern Mediterranean and the fjord zone of Northern Europe. In India they appear to have acquired very little taste for the sea; and if all their contacts with the deep had been as little calculated to encourage men to maritime life as those afforded by the peninsula of Hindostan, this race would never have won the empire of the world from its ships' decks, as it has done.

At present these harborages of the glacial belt are of less importance to the development of sea-craft than they were of old. Yet even now it is to such regions that we look for the sailors of our race and not to the more southern and less indented shores.

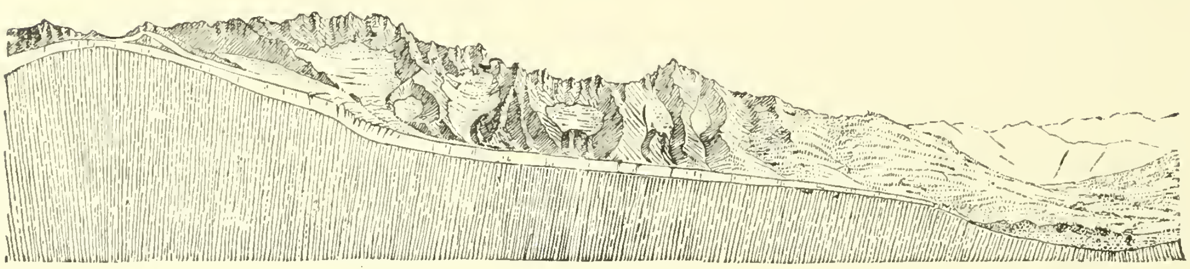
There are many other questions brought up by the study of glaciers. Among these we may note the effects of the vast fleets of icebergs which must have crowded down towards the tropical seas during the glacial periods; the possible bridging of the North Atlantic and Northern Pacific oceans by the glacial sheet, so that the northern continents were united by the ice bridge. These problems might well deserve attention if enough facts had yet been brought together to make their discussion possible.

There can be no doubt that this field abounds in profitable subjects of inquiry upon which the investigator has not yet begun to labor.

We cannot take leave of the interesting question of glaciation without giving an answer to the natural inquiry concerning its future occurrence on the earth's surface. The geologist is necessarily a student of a past so rich, so full of problems, that he finds as a rule scant time to consider the future of the earth. There can be no doubt, however, that all the forces that have proved efficient on the earth in the past will act upon it in the time to come. The whole history of the earth is a record of cyclical change. Whirl on whirl the times recur towards their beginnings, always lifting the life that they bear with them farther on its upward journey. There is no sign that the earth is in its decadence; every element of its structure is as strong as it ever was, and the end of the history seems no nearer than in the earliest ages. Many ice sheets have swept over the continents in the past, and many are probably destined in the future to drive life away from the circumpolar lands.

There is no reason to believe, however, that any such new period of ice is soon to come upon the earth. If such periods depend upon the eccentricity of the earth's orbit, or upon the change in the distribution of the lands and seas,

they are clearly far away from our time. The history of the past shows us that glaciation is an occasional and not a frequently recurrent phenomenon. It is therefore with reason that we regard it as belonging in the distant future. The world is just through one of those great paroxysms, and man may disappear before it is subjected to another.



Ideal Section of a Glacier from Head to Foot.

GLOSSARY

OF TERMS USED IN THIS AND OTHER WORKS ON GLACIERS.

Alluvium. The deposits from fresh water made principally along the banks and in the deltas of rivers. Contrasted with *Diluvium.*

Ås (pl. *Åsar*). See *Kame.*

Bergschrund. The fissure formed where the névé is riven by its passage onto steeper slopes.

Boulder. A fragment of rock transported from its parent ledge by glacial or other action.

Boulder Clay. Unstratified clay containing boulders, pebbles, and sand, brought to its present position by ice action, and retaining the structure given when the ice melted.

Crag and Tail. The shape of hills given by the greater wear of the side against which the moving ice stream impinged.

Crevasse. A fissure in the ice formed under the influence of various strains.

Diathermancy. A quality of ice that permits the passage of heat through its mass without producing sensible melting. (Adj. *diathermous.*)

Dilatation. The expansion of ice from the freezing of water in fissures.

Diluvium. Masses of waste which are now recognized as the result of glacial action, but which, when the term was applied, were supposed to be due to great floods.

Dirt Bands. Transverse depressions on the glacier, formed by the irregular movement of ice in the séracs, or ice-falls, into which sand and gravel have fallen, or have been washed by flowing water. On account of the faster motion of the middle, they gradually assume the form of curves, with the apex down stream.

Drift. A general term applied to all the waste due to the last glacial period.

Drift { *Modified.* / *Secondary.* / *Stratified.* } Glacial drift rearranged by subsequent water action.

Drift, Northern. A general term for all the glacial waste in the Northern Hemisphere, on account of its source being generally to the north.

Drift, Glacial, Original, Unmodified, Unstratified. Drift as it was left by the glacier. Contrasted with *Modified Drift.*

Drumlin. See *Lenticular Hill.*

Erratic, as a noun, equivalent to *Boulder;* as an adjective, indicating that the mass has been brought for some distance by glacier or iceberg.

Eskar, or *Esker.* See *Kame.*

Fjord, or *Fiord.* A deep indentation of the sea-coast, such as abounds in Norway, Scotland, Maine, and elsewhere.

Fjord Zone. A region in high latitudes, and generally on Western coasts in which fjords abound.

Firn. German equivalent of *Névé*, which see.

Floe. A sheet of ice several feet in thickness, such as forms on the surface of Arctic seas.

Floe-berg. A thick mass of floe ice heaped together by the collision of floes with each other or with the shore.

Forest-bed. Plant-bearing beds that are at many points found intercalated amid glacial deposits.

Glacial Lake. A sheet of water owing its existence to the effects of the glacial period. They are of two classes, — those excavated in the rock, and those produced by the irregular deposit of heaps of drift.

Glacial Period. A division of geological time when glaciers had a much wider extension than they have at present. There have been many such periods.

Glaciation. The work done by the glacial sheet in its progress over the land or over the floor of the sea.

Glacier. A mass of ice moving slowly down a mountain slope or valley.

Iceberg. A fragment floated away from the end of a glacier, where it projects into the sea.

Ice-floe. See *Floe.*

Ice-foot. Ice formed along the shores of the polar regions; also called *ice-belt.*

Interglacial. Occurring between the beginning and end of an ice period. Other prefixes compounded with "glacial" are *pre, post,* and *sub.*

Kame, also called *Ås,* or *Eskar.* An irregular hill or ridge of sand, gravel, and boulders, accumulated in a more or less distinctly stratified arrangement at the front of a continental glacier, and therefore to be included under morainal deposits.

Lenticular Hill. An arched deposit of unmodified drift or boulder clay, much in the form of an inverted boat.

Moraine. A mass or line of detritus carried along by or deposited directly from a glacier.

Moraine, Ground. The mass of débris accumulated under the glacier.

Moraine, Lateral. Waste pushed out or accumulated at the side of an ice stream, as in Swiss glaciers.

Moraine, Medial. A line of waste in the middle of a glacier, produced by, and extending below the junction of two lateral moraines.

Moraine, Terminal. Heaps or ridges of débris deposited at the front of a glacier, in lines transverse to its motion.

Moulin. A well-like shaft in the glacier, through which water from the surface of the ice finds its way to the bed of the stream.

Névé, also *Firn.* Glacial matter in a transitional granular state between snow and ice, found on mountain slopes between the upper snow-fields and the glaciers below.

Paleochrystic Sea. A name given to the ice in the Arctic Ocean, where the land barriers prevent its floating south, and admit its freezing to great depths.

Plasticity. The assumed quality of ice that would permit one particle to slide over another, as in tar.

Regelation. The property of ice whereby two fragments will freeze together when pressed against each other.

Roche Moutonnée. A boss or ledge of bed-rock, rounded by the action of a glacier.

Scratches, or *Striæ.* Marks made upon rocks by the motion over them of other rocks contained in a glacier.

Séracs. Large fragments of ice between the numerous crevasses of a glacier on a steep slope.

Shock and *Lea Sides.* The sides of a hill exposed to, and protected from glacial erosion. See *Crag and Tail.*

Subglacial. Beneath the glacial sheet.

Terrace (when used in connection with this subject). A stratified deposit of fine rearranged glacial waste with an approximately horizontal surface.

Till. Generally synonymous with *Boulder Clay.*

Viscosity. The assumed property of ice whereby one particle flows over another. Nearly synonymous with *Plasticity.*

LIST OF WORKS ON GLACIERS AND GLACIATION.

THE following list of works and articles on glaciers, drift, and allied subjects makes no claim to be considered complete, as the literature in this department of geology is very extended; but to the student who wishes to increase his acquaintance with the more important researches and compilations on glaciers and glaciation, it may prove of service as a guide.

The references are arranged, first, geographically; then alphabetically by authors' names. For separate works the author, title, place and date of publication are given. Periodicals and publications of societies are referred to by abbreviations explained below, and further details are given in the following order: date (as 1846), series (4°), volume (xli.), page (316).

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ACTES SOC. HELV. Société helvétique des Sciences naturelles (= Allgemeine schweizerische Gesellschaft für die gesammten Naturwissenschaften). Actes (= Verhandlungen), 1828.

ACTES SOC. LIN. BORDEAUX. Actes de la Société linnéenne. Bordeaux, 1830.

ALPINE JOURN. The Alpine Journal. Published by members of the Alpine Club. London, 1863.

AMER. JOURN. SCI. (Silliman's) American Journal of Science and Arts. New Haven, 1818.

AMER. NAT. The American Naturalist. Salem, Boston, Philadelphia, 1867.

ANN. CHIMIE. Annales de Chimie. Paris, 1789.

ANN. CLUB ALPIN FRANÇ. Annuaire du Club alpin français. Paris, 1874.

ANN. MINES. Annales des Mines. Paris, 1816.

ANN. N. Y. LYC. Annals of the Lyceum of Natural History. New York, 1823.

ANN. SCI. GÉOL. Annales des Sciences géologiques. Paris, 1842.

ANN. SCI. NAT. Annales des Sciences naturelles. Paris, 1824.

ANN. AND MAG. NAT. HIST. Annals and Magazine of Natural History. London, 1838.

ATTI SOC. ITAL. MILANO. Società italiana di scienze naturali. Atti. Milano, 1860.

AUSLAND. Das Ausland. Stuttgart, 1829.

BIBL. UNIV. Bibliothèque universelle des sciences, belles-lettres et arts. Genève, 1816.

BIBL. UNIV. ARCH. Archives des sciences physiques et naturelles. (Supplement to the preceding.) Genève, 1846.

BR. ASS. PR. or REP. British Association for the Advancement of Science. Reports (including proceedings), 1831.

CANAD. NAT. The Canadian Naturalist and Geologist. Montreal, 1857.

CLUB ALP. ITAL. BOLL. Club alpino italiano. Bolletino trimestrale. Torino, 1865.

COMPTES-RENDUS. Comptes-rendus hebdomadaires des séances de l'Institut de France: Académie royale des sciences. Paris, 1835.

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DEUT. ALPENV. ZFT. Deutscher Alpenverein. Zeitschrift. München, 1869.

DEUT. GEOL. GESELL. ZFT. Deutsche geologische Gesellschaft. Zeitschrift. Berlin, 1849.

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PHIL. TRANS. Royal Society Philosophical Transactions. London, 1665.
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PROC. BOSTON SOC. NAT. HIST. Proceedings of the Boston Society of Natural History. Boston, 1841.
PROC. GEOL. SOC. The Geological Society of London. Proceedings, 1826.
QUART. JOURN. GEOL. SOC. The Geological Society of London: Quarterly Journal, 1845.
REV. DES DEUX MONDES. Revue des Deux Mondes. Paris, 1831.
REVUE SCI. Revue scientifique. Paris, 1864.
SCHW. ALPENCLUB, JAHRB. Schweizerischer Alpenclub. Jahrbuch. Bern, 1864.
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TRANS. CAMBR. PHIL. SOC. Transactions of the Cambridge Philosophical Society. Cambridge, England, 1821.
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LIST OF PLATES.

We naturally turn to Switzerland for illustrations of Glaciers. There glaciers are well developed, and have been carefully studied; and in these modern days of easy travel, there they are more accessible than anywhere else in the world. In the Alps alone, we find facilities in travelling and comfort in living, accurate maps of the country and sufficient descriptions of its features, together with scenery of the most picturesque description. Within the limits of a morning's walk from an inn one may reach the eternal snow of the mountains, whence all sight of villages, fields, and trees is lost, and only snow and ice, rock and sky, may be seen. While the peaks are not so high as those of other mountains, the valleys are often so deeply and abruptly cut that the effective height of the summits, as seen from below, is rarely surpassed even in mightier ranges; and although this region is in medium conditions of climate, the relations of altitude, precipitation, and temperature are so well adjusted that all phenomena of snow-fields and glaciers are seen in complete development. The only attractive element that is missing is that which comes with the exploration of an unknown country. Switzerland has been thoroughly tracked over by its active summer visitors, and we must now go to the Himalaya, the Andes, or our Cordilleras to make new paths. Not a small advantage, however, in favor of Switzerland, is the ease of finding good illustrations of its scenery; in climbing about, the photographers are not very far behind the members of the Alpine clubs, and fine pictures may be had of the more striking features of all parts of the country. It is to be expected, therefore, that most of the following plates should represent scenes in Switzerland; but in order to make the series of illustrations of more general character, a number from other mountain regions have been added at their proper places in the set. Their arrangement is such as to show, first, a general view of glacial form; second, detail of structure from greater to less altitudes; and, third, effect of glacial action. These are followed by a map showing the present distribution of glaciers, and the larger areas that they formerly occupied.

No. of Plate.	Photographer.	Title.	District.
IX.A.	Frith, of London	Medial moraines of the Aletsch Glacier	Aletschhorn Group, Central Switzerland.
IX.B.	" "	Medial moraine of the Viescher Glacier	" " " "
X.	Braun	The Hüfi Glacier	Maderan Valley, Central Switzerland.
XI.	Knudsen, of Bergen . . .	Buer Glacier	Norway.
XII.	Braun	The Allalin Glacier and the Mattmark Lake	Saas Valley, near Monte Rosa, Switzerland.
XIII.A.	Bourne & Shepard, Calcutta	Foot of a glacier in the Buspa Valley .	Upper part of the Buspa Valley, Himalaya.
XIII.B.	Knudsen, of Bergen . . .	Foot of the Naesdals Glacier	Nordfjord, Norway.
XIV.	Braun	Ice cave of the Grindelwald Glacier . .	Bernese Oberland, Switzerland.
XV.A.	Unknown	Recession of the Glacier du Rhone . .	Head of the Rhone, Switzerland.
XV.B.	"	Recession of the Glacier d'Argentière .	Near Chamounix, Alps of Savoy.
XVI.A.	"	Merjelen Lake	Aletschhorn Group, Central Switzerland.
XVI.B.	"	The Tschierva Glacier	Bernina Group, Eastern Switzerland.
XVII.	Braun	The Grimsel	Head of Hasli Valley, Central Switzerland.
XVIII.	Jackson, U. S. Geol. Survey of the Territories . . .	Roches Moutonnées Creek	Colorado, Sahwatch Range of the Rocky Mts.
XIX.	Jackson, U. S. Geol. Survey of the Territories . . .	Arkansas Valley moraines	" " " " "
XX.	Heliotype Printing Co. . .	Glacial striæ	Chazy, New York.
XXI.	" " " . .	Slickensides and pebbles	Massachusetts.
XXII.	Bourne & Shepard	Weathered boulders	Central India.
XXIII.	Heliotype Printing Co. . .	Drift sections	Revere, Mass.
XXIV.	" " " . .	Lenticular hills	" "
XXV.	Projection from Stieler's Atlas	Distribution of glaciers.	

PLATE I.

MONT BLANC AND THE GLACIER DES BOSSONS.

NEAR the end of the day's diligence ride from Geneva to Chamounix, the traveller, coming to the Alps from the west, passes the spot whence this view of the Glacier des Bossons is taken : it is his first near approach to a large ice stream descending from high snowy mountains, and serves well to introduce this series of illustrations. The relative heights of the mountain summits from which the snow begins its descent is not appreciated on account of looking upward from the valley. Mont Blanc, the highest of the Alps, is from this point apparently lower than some of the nearer peaks. One hardly realizes that it is two miles higher than the bottom of the valley : it seems overtopped by the Dôme and Aiguille du Gouté to the right. On the left, the Aiguille du Midi presents so steep a northern face that it scarcely holds snow for two thousand feet below its serrated summit. Between these extremes lie two great snow basins, opening into steep ravines falling to the north. From Mont Blanc and the Dôme du Gouté, the Glacier de Taconay descends behind a wooded spur that hides it from view. From the Aiguille de Saussure and the neighboring peaks, the Glacier des Bossons gathers its névé, passes across a shelf known to the guides as the "plateau," and then pushes its foot well down the mountain flanks before us. The surface of the plateau is not seen from the valley, but its front shows as a line across the slope. Taken as a whole, this glacier is of comparatively simple form : it receives no important branches to the main mass, so that medial moraines are not seen on its surface. The latter part of its course is very steep, and the surface is consequently greatly broken, so as to be quite impassable, while above on the plateau, though it is deeply rent, there is less difficulty in finding a way across it. On account of its abundant supply of snow and steep descent on the shaded slope of the mountains, the foot of the glacier reaches a lower level than any other in this region of the Alps. The end of the ice stands at about three thousand six hundred feet above the sea, or two hundred feet above the valley, at this point. In the Bernese Oberland, the Grindelwald Glacier, by a still more fortunate combination of favorable conditions, descends to about three thousand three hundred feet, — the lowest in Switzerland.*

The terminal moraines are well seen in the light and shadow of the afternoon sun. On account of the recent shrinking away of the ice, they project some distance into the valley beyond the present ending of the glacier. They are hills of considerable size, although quite overshadowed by the great mountains on whose flanks they lie. Just under the edge of the "plateau" other abandoned moraines are seen. Plates V., VI. A, and VIII. A, illustrate some parts of this glacier more in detail.

* These altitudes are probably inapplicable at the present time, owing to the recent rapid retreat of the Swiss glaciers.

PLATE II.

THE GLACIER DE TALÈFRE FROM THE JARDIN.

From the valley of Chamounix we see the snowy mountains far above us, as in Plate I. To gain a nearer acquaintance with their middle heights, the visitor should ascend the flank of the range to the Montanvert, choosing the early morning, while the path is still in shadow, for the walk. The day may be entertainingly spent on the Mer de Glace, which here emerges from its deep mountain reservoir to fall in séracs to the valley below (see Plate VIII. B). A hotel close by gives comfortable quarters for the night. The day following, not later than sunrise, he should set out on a walk up the glacier, and in a few hours he will reach the Jardin, from which the opposite view is taken, looking back over the last mile of the icy path. The Jardin is an isolated rocky island in the glacial stream, so named because it bears a few Alpine flowers on its sunny slopes late in the summer. It reaches up through the ice and snow that are spread out on all sides, and stands like an island alone in the midst of a great frozen amphitheatre, shut in by steep rock walls. The only outlet is directly in front. From the Aiguille du Moine, just without the view on the right, this impassable wall extends around behind us, through the Aiguille Verte and the Aiguille de Triolet, and then forward again through the Aiguille de Talèfre, from which a spur descends on the left of the view. The circumference of this oval basin measures about six miles. All the snow and rain that fall within it pass out in the form of a glacier and its accompanying water streams through the gap before us of about half a mile in width. It is known as the Glacier de Talèfre. Early in the season the snow lies heavily on the ice and hides its surface; but later, by July or August, this melts away, and the moraines are revealed as long curved lines. Those coming from the left may be traced up to several spurs below the Aiguille Verte; from the Jardin itself, a less conspicuous line of stones and débris is dragged out by the flow of the ice. From the position of these moraines at the gap where they pass out of sight down to the valley below, it may be inferred that the area drained to the right of the Jardin is smaller than that to the left, and that a still smaller area supplies the ice flowing between the main and the Jardin moraines. Looking closely at this last-named division of the glacier, some of the curves of flow may be seen, — faint U-shaped lines, with the curve turned down stream, showing the faster motion of the middle of the ice.

In descending from the Jardin, the solid ice is crossed to the left of the gap; then the path follows down the lateral moraine, as the glacier is completely shattered into wild séracs. Below, it meets the Glacier de Lechaud, about half its size, coming from the left out of the basin between the Aiguille de Talèfre and the Grandes Jorasses. Shortly below their junction the two streams meet the great Glacier du Géant, or du Tacul (see Plate VII. B), of more than double their united strength. It comes from a broad valley heading against Mont Blanc itself, draining several smaller basins that lie between the Grandes Jorasses and the Aiguille du Midi. Below the confluence of these several glaciers there are no other tributaries; the single stream, known thence as the Mer de Glace, extends about four miles farther along a moderate slope. It ends under the Montanvert, where its final séracs are known as the Glacier des Bois. The Glacier de Talèfre shows but a single medial moraine after passing its outlet, the several lines shown in the plate having been united in one in the healing of the shattered mass. It may be then traced nearly to the end of the Mer de Glace, where it becomes confused with several others, as is shown in Plate VIII. B.

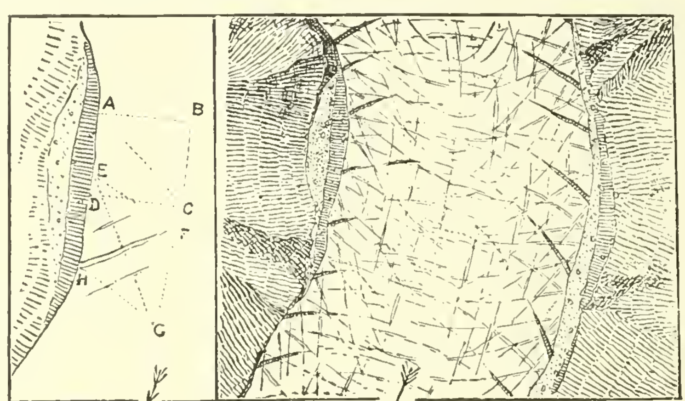
PLATE III.

THE ALETSCH GLACIER FROM THE EGGISCHHORN.

As will be seen by consulting the map on the following plate, the Eggischhorn commands a view of almost the entire length of the Aletsch Glacier. Part of the upper snow-field is hidden by the Dreieckhorn, and the end of the ice sinks out of sight under the Bel Alp, but between these extremes the long river-like glacier lies before us. It is peculiar in having no important branch below the Faulberg. Several small glaciers or snow patches lie on the flanks of the Walliser Virschhörner and Dreieckhorn, but now these contribute little more to the main stream than rock and gravel, which form a strong lateral moraine. That on the nearer side of the valley is overwhelmed by the ice at the curve just above the Merjelen Lake. On the opposite side the ice has less tendency to press on its banks, and furthermore the moraine there is prolonged by the assistance of the Middle Aletsch branch, from a basin of moderate size under the Great Aletschhorn.

The medial moraines are described with Plate IX. A. Their increasing distinctness down stream is owing to the melting away of the snow and ice that conceals their detritus nearer the névé region. Two other results of glacial motion will be described here, — the lateral crevasses, and the banded structure of the ice.

The crevasses are seen in several parts of this, and in many of the other plates; and if those extending inward from the margin of the ice be examined, they will be found directed up stream. This was at first taken to be proof that the margin of the glacier moved faster than the middle, but later it was perceived that it depended on precisely the opposite relation of velocities, as will be understood from the accompanying figure. Let *A B C D* represent the surface of a rectangular block of ice at the margin of a glacier *A H*; its inner side, *B C*, will move faster than the outer, *A D*, and after a time the block will have moved down to the position *E F G H*, where the lozenge shape is produced by the greater velocity of its inner part. The diagonal *A C* has become *E G*, and evidently, of all the lines in the block, this diagonal is the most elongated. The ice, being unable to stretch to accommodate itself to this tension, is forced to break, and so a crevasse, *H F*, is formed, at right angles to *E G*. Crevasses formed on suddenly increased slopes are shown in Plate VII. and VIII. They are also pictured on a small scale in the fall of the Middle Aletsch Glacier on the opposite plate.



The banded structure of the ice (see Fig. 5, page 20) is seen in the upper half of this glacier as faint zigzag lines, somewhat like the grain of wood when cut obliquely. From the surface of the glacier itself these are scarcely visible; but on looking from a height above it, their slight shading is easily recognized. They furnish the most direct natural proof of the faster motion of the centre than of the margin of a glacier. When it is possible to trace them to the upper part of the stream, they are found to originate in the first set of transverse crevasses. Dust blown by the wind, and morainal detritus that may chance to be on the surface collect in these fissures, so that when the séracs of the broken stream are brought together below the fall (see Plate VI. and VII.), their surfaces of junction or regelation are marked by ice of less purity than the rest of the mass. The banding here is indistinct, but when seen it extends directly across the line of motion. Farther down stream, the excess of motion in the medial line of the surface carries the middle of the bands down faster than their sides, and the farther they are carried from their point of formation, the more they are drawn out and bent downward. At last they become in the greater part of their length almost parallel to the banks of the valley, and are so shown in Plate X. In case several streams unite, each one possessing its own set of bands, they give rise to the zigzag lines well represented in this plate. In passing an ice-fall they are almost destroyed.

PLATE IV.

THE ALETSCH GLACIER AND ITS SNOW BASIN.

The Swiss Federal Map, completed about twenty years ago under the direction of General Dufour, consists of twenty-five large sheets, each twenty-seven by nineteen inches in size, on the eighteenth of which the accompanying map of the Aletsch Glacier is founded. In examining the map, look first at the total area drained by the stream that issues from the foot of the glacier, and follow around its divide or parting line that separates it from the adjoining snow fields. It will be found of irregular outline, like a river basin, which it resembles in most features. Next let us examine the subdivisions of the snow basin. The great ice stream descends from three extensive snow fields: one sloping off from the Viescher Grat, a second from the Jungfrau, a third from the Mittaghorn. On the east and west these fields are connected by snow passes with the névés of adjoining basins, — the Grünhornlücke, leading to the Viescher Glacier (see Plate IX. B), and the Lötschenlücke, to the Lötschen Valley. Before the névé from these upper fields reaches its narrow outlet it is probably well compacted into ice, and thence onward continues as a massive ice stream. On its way it receives two small branches, but their supply is so small that they have scarcely any effect on the main stream. The ice is all destroyed by melting and evaporation about twelve miles from its great basin, at an altitude of about five thousand feet. For so great a supply reservoir, this is a comparatively high level for its ending. It is due to its long, gentle descent of the sunny southern slope of the mountains.

It is to be regretted that the moraines could not be shown. On the Swiss map they are omitted, except in one or two places, where they seem inaccurate. As may be seen from Plates III. and IX. A, they are very distinct, and are worthy of special study.

On account of its great size, the Aletsch Glacier is not so easily examined as some of the smaller ice streams of the Alps, but the excursions over it are full of interest. There are commodious hotels on the sharp spur west of the end of the ice known as the Bel Alp, and on the southeast flank of the Eggischhorn. From the former the glacier is seen, as in Plate IX. A; from the latter it is hidden, but an hour's climb takes one to the summit of the peak, whence the entire length of the stream is in sight, as in Plate III., from the snowy Jungfrau to the dark gorge under the Bel Alp. From either of these starting-points the ice is within easy walking distance, and much time may be well spent in examining the peculiarities of its surface. The névé fields are too large and remote for frequent study. They are seldom traversed, excepting on the difficult excursions that lead out by the Lötschenlücke, or over some of the passes by the Jungfrau or the Mönch to Grindelwald. Sometimes the night is passed in a little hut built for such occasional shelter at the foot of the Faulberg. Very similar scenery to that of the Great Upper basin, though on a smaller scale, is found after an easy walk from the Bel Alp up the Upper Aletsch Glacier, — a day's excursion of great interest. At the outset the recent shrinkage of this branch stream is very apparent. From the freshness and sharp form of the abandoned moraines, one may judge that the retreat has only just taken place. In either branch of the Jägi Glacier is seen a good example of a mountain amphitheatre, — a desolate solitude, the sides rising to steep, rocky walls, impassable save at a few outlets, the bottom deeply buried in snow and ice that slowly find their way down the draining glacier. Snow, névé, crevasses, moraines, all may be seen here in perfection; only séracs are absent. It is worth the effort to ascend the long snow slope to its rounded top, as at the Beich Grat,* to gain a view of the basin from one of the few accessible points on its rim, and to look out on the surrounding mountains, — a wilderness of black rock, peering through dazzling snow under a sky of deep dark-blue.

* On the Dufour map this is spelled "Birch Grat."

PLATE IV

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THE ALETSCH GLACIER AND ITS SNOW BASIN.

PLATE V.

THE GORNER GLACIER FROM THE GORNER GRAT.

THE Gorner Glacier is a long stream rising to the left of Monte Rosa, and receiving on its course a number of branches from the great snowy range to the south. From the side of our point of view, it has no tributaries : the ridge holding the Riffelhorn and Gorner Grat, and culminating in the Stockhorn farther east (not shown here), is precipitous on its southern flank, and sheds its small snow fields into the Findelen Glacier in the next valley northward. It is therefore an easy matter to approach this great ice stream near the middle of its course, and view, from a point reached by a plain, open path, its upper snow fields as well as the confluence of the glaciers they send forth, all at no great distance. If the north side of the valley were bordered by mountains equal in height to those on the south, this opportunity would be denied us.

The long narrow moraine lines are the most striking features of the view ; excepting the nearest one, they may all be traced to their sources, and in most cases will be found to lead up to a spur that divides two adjacent snow fields. Their form and that of the lateral moraines from whose union they extend are lost in printing the photograph long enough to bring out the details of the dazzling white snow surface above. The scale of tints from paper white to ink black is of less range than from snow light to rock shadow ; hence in photographs of mountains that include such strong contrasts in their illumination, it is generally necessary to sacrifice one end of the scale in order to appreciate the other. To give a better idea of distance than may be obtained from the foreshortened slopes of the plate, it may be stated that from the point of view across the main glacier is about half as far as from the foot of the Schwärze Glacier to the summits of the Zwillinge ; and from the crest of Monte Rosa to the foot of its glacier, between two equal spurs, is about as far as from there to the larger black spur under the Breithorn.

The details of the smooth snow fields and broken and reunited ice slopes should be studied again after looking at the following plates. Here we may limit the description to the surface of the main glacier and its moraines ; the latter will be designated by numbers counting from the nearer to the farther side.

The moraines that rise from bold spurs and distinctly mark the line of junction of two confluent streams are of the ordinary type. Of this kind are the fourth and fifth ; another from the larger spur under the Breithorn, at the left of the Unter Theodul Glacier, is hidden by the convex surface of the main stream. The third moraine gradually fades away as it is traced upwards ; it seems to lead to the lowest spur of the Lyskamm, but the greater part of its stony line is dragged by the ice from a ledge below the general surface of the Grenz and Zwillinge glaciers, where they meet ; it remains hidden till the surface melting and a possible slight working of the fragments from below upwards in the ice exposes it to sight. The first moraine is of this subglacial origin, though not so seen in this view ; it gradually makes its appearance on the glacier between Monte Rosa and the Stockhorn, although no ledge or spur whatever is visible. The head of the second moraine is imperfectly shown on account of its distance ; on closer examination it is found to divide into two branches, one of which runs to either of the spurs at the foot of Monte Rosa. The glacier from this mountain is seen only above the point of branching in the moraine ; this is because so small an ice stream is entirely overwhelmed and drowned by the greater volume of the Grenz and Gorner glaciers on either side. The rule that the number of medial moraines equals the number of confluent glaciers less one is in this case broken, except for a short distance below the confluence. A little pond is sometimes held in the hollow above the junction of the greater glaciers.

The first moraine is conspicuous for its remarkable irregularity, especially at two points in the foreground, where it broadens as if thrown up by an eruption from below ; and to some such motion, though not of a violent kind, the disturbances are probably due. Each may mark some decided irregularity in the bed of the glacier not yet worn down, which causes the stream to eddy in its passage. A reversal of the direct downward motion has lately been observed in one of the Swiss glaciers ; for a short time in the day the surface moved up stream by a small, though observable amount. It is probable that observations on a disturbed part of the ice, as shown here, would detect a similar irregular motion.

At several places on the glacier its surface is broken by shallow pits, known as " moulins." These also seem to mark inequalities in the bed of the stream ; they are formed in definite positions, and after their formation slowly disappear as they float down stream. The scar of an old moulin is generally visible a few hundred feet below one formed a year later. Streams fed by surface melting often find their way down the moulins, and their great depth may be estimated by the long-continued rattling of a stone thrown down the blue shafts.

PLATE VI.

THE UPPER PART OF THE GLACIER DES BOSSONS.

In the descent from the high snow fields of the Mont Blanc group to the plateau of the Glacier des Bossons, the ice on the steeper slopes is broken into a most irregular confusion of massive fragments. They are of all sizes and forms, separated by crevasses of varying depth and width, making an extremely uneven surface, — one that, when covered with a loose coating of snow, presents great difficulties to exploration. On the snow fields and névé above, a more or less even surface is found; and to a certain extent the same is seen on the more gently sloping glacier below. Here it has completely disappeared. The change from the smooth surface above to the irregularity shown here comes from excessive rending of the mass, and is due to the difference of motion of its parts. The transformation from this rough surface back to one of comparative smoothness is more surprising: it is a peculiar property of glaciers, and results from the facility with which the ice welds its broken surfaces together. On reaching the foot of the slope, a slower motion is resumed; the separate masses crowd on one another, the crevasses are closed, their sides pressed together, and the rents are firmly healed. The whole mass becomes more or less closely united, and so remains until new tensions farther in its course tear it apart again. It will be readily understood that the breaking takes place where the slope of the ice increases, that is, at the convex path of its descent; while the crowding together will occur at the change from steep to gentle slope, or in the concavities.

The group of men in the foreground may be briefly alluded to. They are probably the guides or porters that accompanied the photographer on his high excursion, for their appearance even in silhouette hardly indicates the tourist. The ladder which they carry is, aside from its ordinary use, the most portable form of bridge for crossing crevasses. The ice-pick, which in higher journeys replaces the alpenstock, is often needed to cut steps in the ice or névé in scaling its steeper faces. All the men are strung together on a rope, tied around the waist, so that if one of the party falls through the treacherous snow cover of a crevasse, the others can lift him out again. A summer hardly passes in Switzerland without accidents resulting from the neglect of this simple precaution.

Some fine, light, zigzag lines crossing the plate are not in the ice itself, but are slight imperfections in the photograph.

PLATE VII. A *and* B.

THE PLATEAU OF THE GLACIER DES BOSSONS.

As the snow and ice of the supplying fields reach the foot of their first steep slope (Plate VI.), and begin to move across the plateau on the mountain flank, the decrease in motion causes the broken parts to press on one another and reunite. The evenness of this new surface is in strong contrast with the shattered mass above, and in the concave slope of the middle distance it remains unbroken; but as soon as the line of descent changes curvature and becomes convex, long narrow crevasses make their appearance at the edge of the plateau, opening at right angles to the line of flow, and deepening and widening as the greatest bending is reached. These are due to the greater tension at the surface of the glacier over that at the bottom; as the ice cannot stretch, it breaks. Within the limits of the view, the evenness of the plateau is not lost, though its continuity is quite destroyed.

From the absence of snow in the foreground, it may be inferred that the plate represents the glacier as seen late in the summer, when after considerable melting the solid ice is disclosed. Two large boulders lie on it, on their way down to the valley; as they have been carried quietly without friction, they are still angular; and even at the end of their journey they may retain some of the sharp edges of their original fracture, for, excepting a few falls from pedestals or into crevasses, they make the entire distance on the back of the glacier: they are neither scratched nor rounded. A faint moraine may be traced from the left margin of the plate down to the crevasses on the plateau; there it is less distinct on account of the breaking up of the ice. It is noticeable that no lines of detritus are seen leading down from the several rock ledges that rise above the névé or ice surface on the upper slopes. This is because the frequent and heavy snows of these upper regions conceal whatever fragments may from time to time be carried away from the ledges. It is a general rule that moraines are not visible in the snow and névé, though they may exist below the surface. They appear farther down the mountain side when melting has carried off their covering. For the same reason, moraines can be better studied in the late summer months than earlier in the season; and in winter they are entirely buried in snow. (See also Plate V.)

The two rock ledges projecting through the snow in the upper left corner of the plate are known as the Grands Mulets; on the farther side of the lower one (not shown in this view) is a little cabin, where those who make the ascent of Mont Blanc usually pass a night on their way. The summit of the mountain is out of sight, farther to the left. Above the Grands Mulets is the rounded snow mass known as the Dôme du Gouté, and, to the right, the Aiguille du Gouté. They are seen also in Plate I.

THE GLACIER DU GÉANT.

THE features described above are partly repeated here in the upper part of the Glacier du Géant, but with the addition of a snow covering that bridges some of the crevasses. This is the accumulation of several storms, as may be seen from its stratified structure. It was at one time thought that the bands or cleavage of the ice (see Plates III. and X.) was the result of such stratification of the upper snow, but it has been since shown to arise from quite a different cause. The snow here has nearly all fallen from the steep face of the rocks, and collected in the great basin below. The flanks of the peak nearest us, however, hold two long snow slopes, lying at very steep angles. The lower half of the left one has fallen as an avalanche to the ice beneath, leaving part hanging on the rock, and giving at the break a measure of its great thickness.

The plate shows a point on one of the longer and more dangerous excursions of the Mont Blanc region, leading from the valley of Chamounix on the north, over one of the higher passes of the range, to Courmayeur on the south. The route leads up the Mer de Glace, as on the way to the Jardin (Plate III.), but leaves the Glacier de Talèfre to the left, and follows up the Glacier du Géant on the right. The difficulty of the journey comes from its length; the danger, from the chance of falling through a treacherous snow bridge into a crevasse below. It is, however, an excursion to be recommended to those who have had some practice on snow and ice, since it leads through a large and well-enclosed reservoir, so characteristic of Alpine topography, and so essential to the development of large glaciers of the river form. The sharp serration of the walls of the reservoir is also a notable feature of the region, and is excellently shown in the profile of the mountains. Sharp needles like these are the result of air and frost weathering alone, and are never found on surfaces that have borne glaciers. If the ice were stripped from the mountains before us, the height which it had attained would be distinctly marked by the region of rounded rock outlines, while above this limit the form would be angular. It is then only in the valleys where the snow is gathered and converted into deep streams of ice that its erosive power becomes effective. The higher peaks of the Alps escape it entirely. (See also Plates VIII. and XVII.)

PLATE VIII. A *and* B.

SÉRACS ON THE GLACIER DES BOSSONS.

A SHORT distance below the part of the Glacier des Bossons, shown in the preceding plate, and nearer the edge of the plateau, the even upper surface of the ice between the crevasses is lost, and by continuous breaking and melting the irregular forms known as séracs are attained. Here the rending of the glacier rivals the shattering of the mass shown in Plate VI., but it is less snowy than on that upper slope, and there is more of order in its crevasses; they are still distinctly transverse to the line of flow, as in Plate VII. There is no place farther down the descent where these rents are well healed; the glacier follows a long slope almost uniformly steep, and the breaking open of crevasses continues to the foot. The resulting uneven surface may account in part for the absence of medial moraines noted on Plate I. All the stones and gravel that the glacier may have gained from such ledges as the Grands Mulets here fall from the sharp edges of the séracs into the crevasses between, so as to be hidden from view, especially from the valley below. We may still see, on the right, a small amount of moraine rubbish remaining on top of an unbroken block of ice, but a little farther advance will probably break its support, and it will disappear. A pointed sérac in the middle of the plate has thus far escaped complete shattering, and retains its cap of gravel.

Where detritus exists in considerable quantities on a glacier, and is subjected to repeated falling into crevasses, and grinding as the crevasses close, it may well lose some of its angular character, and assume a more rounded form before final deposit in the terminal moraine.

In the distance we may see the upper part of the valley of Chamounix, between the range of the Brévent and the Aiguille Rouge on the left, and the slopes of the Aiguilles du Midi and Verte on the right. The large hotels in the village of Chamounix may be distinguished as a few white dots to the left of a sérac in the middle of the plate. In the distance, at the head of the valley, is the Col de Balme, a pass leading over to the valley of the Rhone. During the height of the glacial period the valley of Chamounix was filled to a great depth by the glaciers which are now shrunk into the lateral ravines, and at that time there was a continuous flow of ice from the Mont Blanc region to the Jura; part of the ice escaped toward the Col de Balme, in a direction opposite to the present line of drainage.

SÉRACS OF THE GLACIER DES BOIS, MER DE GLACE.

WHEN the Mer de Glace passes the Montanvert, it breaks into séracs in the steep fall to the valley of Chamounix, and is known in this lowest part of its course as the Glacier des Bois. In the plate, the Montanvert is the round wooded knoll on the farther side of the stream; a much frequented path leads from it across the glacier, and descends to the main valley by the lateral moraine, and along the mountain side, passing our point of view. The narrow valley through which the snow from the broad basins of the Mer de Glace is drained is seen in profile between the spurs of the nearer Aiguille de Dru on the left, and the farther Aiguille de Charmoz on the right. The latter may be divided into a serrated portion above, and a smoother, rounded outline below, next the ice. The lower part probably marks the height attained by the ice at the time of the maximum development of Swiss glaciers, and its want of angular form is due to their erosive power. (See the explanation of Plate XVII.)

All the moraines from the ridges between the upper collecting basins are here crowded to the nearer side of the glacier, leaving the farther half comparatively clean and white. This is due to the much greater volume of the Glacier de Tacul over all the other branches of the Mer de Glace. A little farther up stream, the separate moraine lines may be distinguished, but here they close on one another and darken half the surface. So dingy and dull is the glacier in its lower course, that disappointment is often felt on first seeing it, when it appears so different from what the imagination pictures as a sea of ice. The progressive shrinking of the Swiss glaciers is shown here, as in almost all the plates. It may be seen on either side of the stream, and especially on the farther bank, in the middle distance, beneath the Aiguille de Charmoz, where a small suspended glacier is the shrunken remnant of a greater mass, that once brought a great quantity of waste to a lower level than its extremity now attains.

The Montanvert is one of the higher points reached by forests, and here shows how far the ice of the glacier extends into the zone of vegetation.

PLATE IX.

MEDIAL MORAINES OF THE ALETSCH AND VIESCHER GLACIERS.

In the comparison often made between glaciers and rivers, the curved direction of flow, as governed by the changing direction of their valleys, is one of the most striking features of resemblance. This is well illustrated in the lower parts of the Aletsch and Viescher glaciers. The views are taken from near the ending of the ice, looking up stream, so that, by foreshortening, the crookedness of the moraine lines which mark the curves of flow is somewhat exaggerated; but this only serves to make the examples more striking.

The Aletsch Glacier is thus seen from the Bel Alp (see Plate IV. and description), looking northeast toward the Eggischhorn, which rises in the middle of the view. The valley of the Merjelen Lake is to its left. Of the surface moraines, one far exceeds the others in size and length. It is probably derived from the Gletscherhorn spur, as this divides the névé fields into nearly equal parts, and its moraine therefore follows the middle of the stream and reaches to its end. Its ridge-like form is due to the faster surface-melting of the ice where unprotected, while under the rock and gravel covering it lasts longer and stands higher. A large part of this ridge is therefore of ice; its dark coating has but little thickness.

A smaller moraine is seen to the right, ending where it runs ashore some distance up stream. This probably comes from the spur leading down from the Mönch. From the relative areas on either side of this spur, shown in Plate IV., one would infer a larger snow supply from the Viescher Grat than from the Jungfrau, and would therefore expect the outer stream to reach farther down the valley than the inner. But it must be borne in mind that the part of the glacier near its banks moves much more slowly than that near the middle, so that the faster motion of the Jungfrau branch may more than compensate for the greater volume from the Viescher Grat. That this is the case is shown by the early ending of the moraine between these confluent streams. Where it runs ashore the branch from the Viescher Grat is all melted away, while the inner branch continues some distance beyond.

To the left of the great medial moraine, several fine lines of detritus may be traced a long way up the stream. They possibly have their rise in the spurs of the Ebnefluh and Mittaghorn. It is to be noticed that one of these suddenly broadens as it ends in the foreground. This would indicate that it is mostly derived from a deeply buried ledge in its course, whose detritus remains well below the ice surface through nearly all its course, and is only disclosed at the end, when melting has carried away its cover. The continuity of these fine lines is a remarkable feature of glacial motion. In a water-stream, confluent branches are well mixed soon after their union, owing to the easy mobility of the particles; in an ice stream each branch remains separate to the end.

On the extreme left, where the stream enters the valley from the north, we may see a thin, broad moraine, which ends after rounding the second spur. This marks the termination of the Middle Aletsch Glacier, — a considerable stream in itself, but so small in comparison with the great glacier as to produce scarcely any effect on it. While it lasts, however, it stands between the main stream and the bank, and so bears most of the retarding effect of lateral friction; and in this way it prolongs the extension of the great glacier.

The Viescher Glacier is simple in its structure. It presents only one well-defined medial moraine, but for its long sinuous form this is unrivalled. Plate IV. shows a part of the névé region of this stream. In both the views we may note, also, the shrunken volume of the ice, as indicated by gray and barren rocky banks and abandoned lateral moraines; the lateral crevasses distinctly turned up stream; and the marked increase in surface roughness and fracture at every change in the direction of flow.

PLATE X.

THE HÜFI GLACIER.

The Hüfi Glacier lies at the head of the Maderan Valley, in one of the less frequented districts of the mountains; it is easily reached by turning off eastward at Stäg, from the road from Lucerne and Altdorf over the St. Gothard Pass; but most travellers do not stop to visit these small lateral valleys, preferring to follow the more frequented roads or to hurry over the mountains to Italy. The view has little of pictorial effect, but is chosen as showing exceptionally well the parallel-banded structure in the ice, and the almost longitudinal direction of the bands in this lower part of the glacier. If the view were taken from above the ice, we should see these fine lines gradually turning in from the margin of the stream and meeting about at the centre in an acute curve. As explained in the text (page 20) and described with Plate III., this is due to the faster motion along the middle line. These bands, near the head of the stream, were stretched almost straight across it; at this point in the valley the motion of the middle has gained on that of the sides by the distance from the apex of a curve back to where the band reaches the side of the ice. It is very seldom that the lines are seen with such distinctness. Besides these bands, we may note the smoothly flowing surface of the glacier; peculiarly so, considering its rather rapid slope: the crevasses in the foreground are evidently of late formation, since they point so clearly up stream; during the short time since they were opened the faster motion of their inner ends has not turned them downwards. Beyond the man sitting in the foreground may be seen an example of the loose contact of the ice at its margin and the bed-rock; observers have been able to crawl into such little caves and note the conditions that obtain under the glacier. The dark streak reaching from the side of the picture out on the ice is probably a dust deposit, possibly the result of an avalanche; that it is only superficial is shown by the white color of the ice in the crevasses that cross it. The great size of all these features may be recognized by comparing them with the two men in the near foreground and with the several others on the same rock surface but close to the edge of the ice.

PLATE XI.

THE BUER GLACIER, NORWAY.

THE glaciers of Norway are, in condition as well as in position, intermediate between those of Switzerland and the great snow and ice area of Greenland. In the low level that they reach, and in some of their great névé fields, they resemble Arctic glaciers; in their river-like form and in the details of their structure they are more closely like alpine glaciers. As yet they have received a small amount of study compared to that given to the Swiss glaciers, and no important question of glacial motion or structure has been solved by observations upon them. The form and distribution of drift in Scandinavia have, however, been closely examined, and in this branch of the subject much original work has been done. In this hilly and mountainous country, once covered by the ice sheet of Northwestern Europe, there is less likeness to Switzerland than to Scotland and Northern Ireland.

The Buer Glacier is in the southern group of snowy mountains in Norway. The view of it given in this plate is taken from the steep mountain slope a short distance above the foot of the ice, where the drainage of a large basin above is discharged through a narrow outlet. In the distance the glacier is much more broken than in the foreground, probably owing to its greater width there, as well as to its steeper slope. Among the upper crevasses a spur gives rise to a medial moraine whose curves indicate the irregular motion of the ice on the approach to its lower course. The abrupt turn made by part of the ice as it enters the lower valley throws the moraine nearer to us than it would lie if the descent had been direct. The amount of detritus in the moraine and the distance it has travelled from its source are not sufficient to admit the formation of a ridge on the ice, as in the Aletsch Glacier (Plate IX. A). The surface is so unbroken in the foreground that the glacier has a peculiar appearance on its final descent, and the crevasses that occur here show well the effect of age; those lately formed being narrow, while the older ones, whose sides have been wasting by melting and evaporation for several months at least, are widely opened. The bands on the ice, which at first seem structural, like those in the Hüfi Glacier (Plate X.), are here probably only superficial streaks formed by the washing of gravel into the crevasses.

PLATE XII.

THE ALLALIN GLACIER AND MATTMARK LAKE.

The Allalin Glacier has its source near the head of the Gorner Glacier (Plate V.), but descends to the northeast into the Saas Valley, instead of to the west toward Zermatt. Owing to its large snow supply and strong slope, it advances so far as to throw a moraine dam across the valley and hold back its streams, thus forming the Mattmark Lake. Several other examples of ponds of this class are found in Switzerland; the Merjelen Lake (Plates III., IV., and XVI. A) is of a somewhat different nature, as there the ice itself makes the barrier.

The lateral moraine of the glacier is the most noteworthy part of this view. The angular form and large size of many of the stones in it are well shown in the foreground, where much of the finer detritus is carried away by the outlet stream of the lake as it escapes under the ice. These stones have been carried or pushed along by the glacier with little friction or for a small distance; still an examination on the spot would probably discover many well-worn and scratched. The position of the glacier's edge so near the ridge of the moraine indicates that no marked recent shrinkage has taken place here, as in the ice-streams shown in most of our views. It is also peculiar in showing that a glacier may advance over its moraine without entirely destroying it. So much is said of the erosive action of glaciers, that this occasional relation is often forgotten. When even a continental glacier advances over an uneven surface, its motion, pressure, and erosion on different parts must be very varied. Fragments worn away at one place will be deposited under another part of the ice, as is shown in trails of boulder clay accumulated near a resisting rock ledge. Drift of an early part of the glacial period is not always carried away by a second advance of the ice.

We may consider here also the form characteristic of deposits from different parts of a glacier. The lateral moraines are of all perhaps the most regular, as may be inferred by examining the even shore line of the ice in Plates III., VIII. B, IX., X., etc. The ground moraine, left under the ice, will be thickest where the pressure and erosive forces are least; if preserved in its original outline, it will be gently undulating, and frequently so disposed as to hold shallow ponds in its hollows; in texture it will be more compact and its fragments will be more scratched than in the other moraines. Small strips of stratified material may result from the action of wandering subglacial streams. The terminal moraine is marked by an uneven, hummocky surface, caused by slight changes in the position of the end of the ice, and consequently of the points of deposition; it frequently contains patches of stratified sand and gravel. When built by a continental glacier, its knobs may be hills several hundred feet high, and its hollows may contain lakes of noteworthy dimensions.

The part played by water in depositing detritus near the foot of the glacier has not yet been considered. During the existence of the great ice sheet the surface of the ground uncovered in its retreat was often imperfectly drained, and temporary ponds and lakes collected upon it, till discharged by further melting. This was especially the case when the slope of the ground was in the direction of retreat; the natural drainage would be then held back by the ice front. In these ponds, sand and clay from the surface or bottom streams of the glacier would be deposited; if the conditions continued long enough, the deposits might grow into broad sand plains. When the ice disappeared, these would be left in positions where the now existing streams could not form them.

In case the water from the glacier has a free discharge, only the coarser sand and gravel will be deposited when the streams leave the surface or bottom of the ice to flow on open ground. If such streams bring with them a considerable amount of detritus, it will collect in irregular hills at the margin of the ice sheet. Kames are probably of this origin (see page 66). By some authors they are ascribed to subglacial streams; by others, to those that flowed on the surface of the old glacier, and collected in their channels all loose detritus they encountered: the second explanation seems best supported by the frequently considerable size of the kame ridges and their irregular direction. Deposits of this kind are of water-worn sand and pebbles, laid down in oblique and confused stratification.

The Aletsch Glacier and the Märjelen Lake

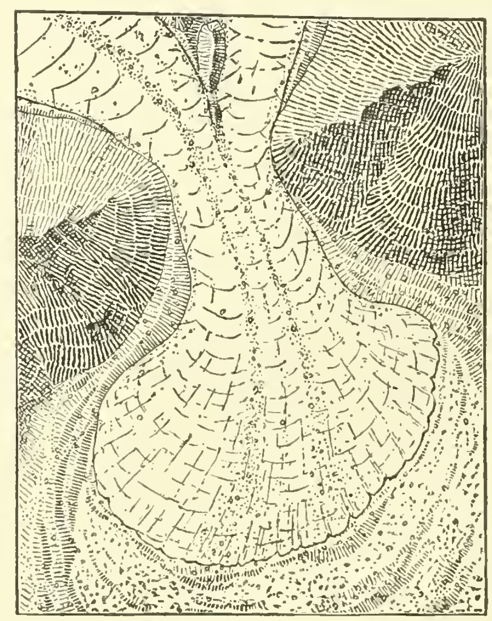
PLATE XIII.

A. THE GLACIER OF THE BUSPA VALLEY, HIMALAYA.
B. THE NAESDALS GLACIER, NORWAY.

Glaciers end rather abruptly where their mass is still considerable, and their thickness as much as thirty or fifty feet. Most of their destruction has been accomplished by melting and evaporation on the long descent from the névé, but this is seldom continued till only a thin edge of ice remains. The termination of a glacier is often in a wall too steep and high to climb, from which large blocks fall, and, shattering to fragments, soon disappear. This is most distinct in glaciers that narrow toward their end. A stream escapes from below their pointed extremity, and aids in breaking off the ice by undermining its base. The forward motion of the ice is also effective in breaking up the front, as soon as it becomes comparatively thin. We may say then that melting and evaporation during the descent in its valley reduce the ice to so slight a thickness that it has no longer strength to hold together in its advance or to bridge over the subglacial stream; then it ends abruptly by breaking into fragments.

De Saussure made long ago a convenient classification of glaciers based on their length and form. Those which lead out from the snow basins and stretch river-like to the lower valleys, are of his first order; those which are but little longer than broad and reach only a little distance from their fields of supply are of his second order. The principal difference between these is in the area they drain. Looking at the subject in a more general way, we may note the following conditions as aiding the extension of a glacier: a large summer and winter snow-fall in an extensive mountain reservoir, with a single exit by a comparatively steep and narrow valley on the polar side of the range, leading down to a cool, cloudy region. Where all these favorable circumstances combine, glaciers will have their greatest length. A considerable altitude or a high latitude is implied in the first condition. The size of the reservoir depends on the topographical peculiarities of the mountains on which the snow falls; single ranges of simple structure are less adapted to furnish snow basins than complex mountain masses like the Alps or Himalaya. The desolate islands south of Patagonia are examples of regions that fulfil the requirement of a cool, cloudy climate.

The great quantity of moraine matter on the glacier of the Buspa Valley is characteristic of several others in the same region, and in general of those in valleys enclosed by easily worn and precipitous rocks. The Z'Mutt and Vernagt glaciers in Switzerland are notable for the quantity of detritus they carry. In Plate A, part of the glacier is broken off too steep to hold the stones and gravel that lie on its upper surface; as they slide and wash down, they leave sandy trails on the ice. Besides these markings, we may note another set, less distinct but of more consequence from being structural instead of superficial; they are seen inclined at a slight angle, beginning within the ice cave and extending a little to the left. They are the dirt bands explained under Plate III.



The Naesdals Glacier, in the Nordfjord of Southern Norway, is peculiarly fissured at its foot, on account of spreading out on a flat surface just after passing through a constriction in its valley. In broadening, it is crevassed radially, as is shown in the accompanying figure, and as melting takes place most rapidly where the ice is opened, it is finally reduced to the irregular form here represented. The moraine on its surface probably comes from the dark isolated ledge in the distance. The great size of the blocks may be measured by two men standing in the middle of the picture. On the right the banded structure of the ice is very distinct; it may be traced to the left, where finer lines of the same origin are seen dipping toward the centre of the stream, as described with Plate III.

PLATE XIV.

THE ICE CAVE OF THE GRINDELWALD GLACIER.

The cave at the end of the glacier is of much greater size than is needed for the exit of the stream that flows from it; for, having reached a level where the temperature is generally considerably above the melting-point of ice, its inner surface offers an additional area of attack, and by breaking and melting it is enlarged to a spacious vault. Venturing into these caves is often attended with danger from the falling of large masses from the roof, and at least one fatal accident is recorded from this cause.

The water that makes its way out at the foot of a glacier may have three important sources. Rain may afford a good part of it at times; surface melting gives a more constant supply; and subglacial springs will furnish a share dependent on the structure of the valley. The latter is of no special interest here; the two former often take part in peculiar erosive actions as they make their way from the surface of the ice by crevasses and moulins to the bottom, carrying with them the sand and gravel from the moraines they have washed down, and frequently falling with destructive effect on the rocky floor beneath. The detritus they carry with them may sometimes be of importance in serving as cutting tools with which the glacier may wear away the rock over which it slides. Where a moulin leads a large surface stream down through the ice, a distinct hollow may be cut out below it. There are many of the so-called "pot-holes" within glaciated regions that are better explained by supposing them the work of streams falling through or running under the former ice-sheet, than by ascribing them to the action of ordinary open-air streams.

The volume of water flowing from the cave at the foot of a glacier is often considerable, and is generally sufficient to keep its way open through the terminal moraines that the ice tends to build across its path. Sometimes the moraine forms a continuous dam, and the stream is held in a pond which rises till it may overflow at the lowest point of the barrier. This relation is not of long duration, since by filling up its basin and cutting down its margin, the lake soon returns to the original condition of a stream. The water is of a chalky or yellowish color as it appears from under the ice, owing to the amount of silt furnished it by the grinding of rocks to powder under the glacier. A very large part of the total eroded material is carried away in this manner, and remains suspended in the stream till some slackening of its flow causes part of the load to fall to the bottom. This is most conspicuous in lakes where the water stands almost motionless, and becomes perfectly clear before assuming appreciable velocity again at the outlet. The glaciers, rivers, and lakes of Switzerland furnish striking examples of these actions. A considerable number of the subglacial streams make a long halt on their way to the ocean, in the lakes that are placed in the lower valleys on all sides of the Alps: above the lakes their waters are turbid, charged with the finest product of glacial erosion, but before the waters of such a stream have advanced half a mile into the lake, the greater part of its sediment has fallen to the bottom, to aid in building out the delta; and an alluvial plain where the stream valley broadens into the lake basin marks the beginning of a change that will in time convert the lake into a broad, fertile meadow. In the present case the stream before us — the Black Lütschine — receives branches from several other glaciers, and unites with the White Lütschine, of similar turbid character, before falling into quiet water by Interlaken, between the lakes of Brienz and Thun. The plain on which this charming town is built is in large part the delta of these glacial streams which have thus divided a once continuous body of water. By ascending from Interlaken to the Schynige Platte, the peculiar course of the Lütschine and its effect on the lakes may be seen from above, as on a map.

PLATE XV.

RECESSION OF THE GLACIERS D'ARGENTIÈRE AND DU RHONE.

From the barren strips of waste uncovered by the recent retreat of the Swiss glaciers, we may gain some idea of the desolate wilderness that must have prevailed in Northwestern Europe and Northeastern America, when the great ice sheet had melted away; a waste of bare rock, sand, and clay, irregular in surface, holding numerous large and small pools of water, and washed by many and strong icy streams, but utterly without life. So it must have remained till a gradual extension of the more hardy plants prepared the way over the desert for others to follow. The present conditions have been very gradually reached.

The diminution of a glacier takes place when the melting is greater than the supply by the downward motion. This condition seems to prevail in modern times not only in Switzerland, but in nearly all countries where glaciers are found. The recession is made up of two motions, — a general retreat, and an oscillation or wavering on this retreat. The first is connected with the passage from a glacial period to a more generally favorable climate; with it may be noted the shrinkage and drying up of many lakes, the decreased volume of many rivers, and the increasingly desert character of regions formerly populous. All these imply a secular diminution in rain-fall. These alternations of advance are but temporary accidents in a general shrinkage of the glaciers. The periods of advance do not occur coincidently in different glaciers; even in neighboring valleys of Switzerland some glaciers will be falling back, while others are pushing their fronts down to lower levels. As yet these variations have not been satisfactorily explained.

Notwithstanding careful comparisons of records of rain, snow, and temperature in Switzerland with measures of the advance and retreat of Alpine glaciers, no sufficient explanation of these oscillations has yet been detected. If this cause be contemporaneous with the change in the foot of the glacier, then the failure of the comparisons must be due either to the unfortunate position of the meteorological stations, most of which are well below the snow-line, or from want of delicacy in instruments and records, or from neglect of some important factor. The first of these defects is of consequence; the others are most likely less important. It is very probable that the records at Geneva or even at the Great St. Bernard give but an untrustworthy measure of the snow-fall on the high mountains; this, most likely, is one source of difficulty. But there is another of greater consequence, which will be apparent when we consider that an excess or deficiency of snow-fall far up in the névé region may not at once make its effect visible at the end of the ice stream in the valley. As already stated, among the various elements of importance in determining the extension of a glacier, the supply of snow outranks all the others. For a given glacier, this depends on the area of its drainage basin, practically a constant quantity; and on the snow-fall, a variable. But from the slow motion of the névé and ice, it will be a long time, perhaps over a century in some glaciers, before an excessive snow-fall in the upper reservoir is felt at the foot of the glacier. The case is analogous to that of a river in time of flood. A rise of the Mississippi at New Orleans occurs a considerable time after a heavy rain or a freshet from melting snow in the upper waters. At much greater intervals the retreat or advance of the foot of a glacier will follow a series of seasons marked by less or more than the average amount of snow. No record exists of sufficient age to test this cause of glacial variation. It cannot be proved until measures of rain, snow, and temperature shall have been kept at least as long a time as is required by the ice of the observed glaciers to move from their source to their foot. Perhaps a careful study of a small glacier of the second order would afford data for an earlier solution of the problem.*

The end of the Glacier du Rhone is now systematically observed; its position is noted every year, and the amount of retreat measured. The light color of the ground in the plate, for a distance about the broad margin, indicates the area so recently abandoned by the glacier that lichens and weeds have not yet darkened it. The form assumed by this glacier below its final séracs is somewhat peculiar: a great quantity of ice is poured down a steep slope into a warm, flat valley; it spreads out in front and laterally, forming a comparatively thin, broad foot; in doing so, it is greatly fissured along radial lines. If the valley were narrow below the séracs, the ice would extend much farther from the foot of its fall. Above it to the right, a faint white zigzag line shows the diligence road, rising from the Rhone valley to the Furka Pass. A superb view of the glacier is obtained in descending this road.

The Glacier d'Argentière displays a more conspicuous abandoned moraine. This glacier rises by the Aiguille Verte, on the slope opposite the Jardin and the Glacier de Talèfre (Plate II.), and descends to the valley of Chamounix, a few miles above the village of that name. Here in the foreground is the hamlet of Argentière, with sufficient accommodation in a small hotel for those who wish to study the district. It is to be noticed that in its former state of great development this glacier approached the broad terminal form still so conspicuous in that of the Rhone. In shrinking, it has dwindled away till its end has become the narrowest part.

* See a paper by N. S. Shaler, in Proceedings of the Boston Society of Natural History, 1881. In press.

PLATE XVI. A *and* B.

MERJELEN LAKE.

Lakes held back by a barrier of ice are at present geographical rarities. They are commonly enough found dammed in by moraines, or held in cavities formed by the uneven deposition of surface drift; the lakes of this last class, though often small, are far more numerous than all others. But in the modern diminished area of glaciers, ice is rarely found properly placed to act as a barrier. The Merjelen Lake before us is one of the few examples known. Its position is shown in Plate IV., where it is seen filling a small lateral valley, free from snow and ice, opening into the great trough occupied by the Aletsch Glacier, which holds back its water. In size it is, when largest, less than a mile in length. Blocks of ice frequently break off from the face of the barrier, and float away as little bergs, reproducing Arctic phenomena in miniature. By accident of melting or moving of the ice that forms the dam, a subglacial outlet is sometimes made for the collected water; this is enlarged by the escaping stream, which flushes the channels under the ice, and carries with it a great quantity of sand and mud. On emerging at the foot of the glacier, it causes a flood, and more or less damage in the narrow valley leading to the Rhone below. The lake is emptied, the bergs are stranded on its bed, and only scattered pools and a little stream are left. Later changes in the glacier close the accidental outlet, and the water collects again. At the time the view was taken, it stood at its highest level. Such accidents were doubtless of frequent occurrence during the glacial period.

The shore line of such a pond, like that of lakes in general, is marked in several ways: a bench may be cut in the steeper banks if the waves have sweep and strength enough; a terrace will be built out where sediment is washed into the water; boulders are dropped there by stranded bergs. Afterwards, when the ice barrier melts away, these benched or terraced shore lines remain, contouring around the sides of an open valley, and marking the levels at which the water habitually stood. The case of this kind that has attracted the most attention is in Glen Roy, Scotland. Many surmises were made as to the origin of the "parallel roads," until Agassiz settled the question by explaining them as the banks of a lake formed by a succession of glacial barriers.*

* A notice of the many publications on this celebrated locality is given in "Nature" for May 20, 1880.

THE TSCHIERVA GLACIER.

At the end of the illustrations of actual glaciers, this plate may serve as a review. Here we have an entire glacier, visible from its snow fields to its terminal moraine, and exhibiting nearly all the characteristic features of a large ice stream. The main reservoir is below the notch in the middle of the upper profile, between Piz Bernina and Piz Roseg on the left and right, whence the ice passes down a steep slope in massive séracs. At the foot of this fall a smaller stream comes from an adjoining basin, and a distinct medial moraine extends downward from the dividing spur. Farther on, toward the foot of the ice, where it broadens and thins, there are strong marginal crevasses. The lateral moraines are of marked distinctness; the terminals are less pronounced within the limits of the view, probably owing to the glaciers being in continual retreat, and not halting long enough to accumulate a ridge of detritus at its extremity. All the ground to the left of the foot is, however, strewn with a heavy coating of morainal material. On the right, the moraine is intensified by the confluence of the Roseg Glacier, of which only a small point is included on the plate. The banded structure of the ice is barely distinguishable.

The Tschierva Glacier is one of several that flow from mountains of the Bernina group in the Eastern Alps; the stream from its foot passes Pontresina, and joins the Inn in the Upper Engadine, between St. Moritz and Samaden. Of late years, part of the constantly increasing travel in Switzerland has turned toward this region, that was formerly but little explored.

PLATE XVII.

THE GRIMSEL.

A striking difference will be found between the outline of the rocky mass behind the Grimsel Hospice opposite, and that of the mountain crests in Plates II., VI. A, and VII. A. The composition and attitude of the rocks are much the same in all the examples; but one has been heavily worn by a deep mass of ice shod with stones and sand slowly grinding over it; the others have never been buried unless in snow, and their forms are due to air weathering and frost. In the latter cases the destructive agents acting on a large mass of comparatively uniform rock concentrate their erosive powers in the cracks and seams that penetrate it, and if these have a generally uniform direction, it will strongly affect the resulting mountain form. To this cause is due the pronouncedly sharp needles, or *aiguilles*, and acutely serrated ridges so characteristic of the higher central Alps that have never been buried in ice; the joints of the rock there stand about vertical; the vertical element in the outline is therefore well emphasized.

With glacial erosion* the result is different. The destructive effects of a heavy mass of moving ice are measured by its depth and consequent pressure, its rate of motion, by the number and hardness of the cutting tools with which it is shod, and by the quantity of water flowing beneath it. The resistance of rocks to glacial erosion will be increased with their hardness and evenness of surface. Angular projections are especially weak, as they feel the full pressure of the onward motion of the ice. An ice-worn surface must therefore be smooth or gently undulating, never sharply angular. Rocky knobs having this characteristic rounded form were called " moutonnées " by De Saussure nearly a hundred years ago, and the term was so well chosen that it has never been supplanted. Quite as characteristic are the smoothly hollowed basins unknown to other forms of erosion. These rock basins are the concavities of a glaciated surface, while the intervening " roches moutonnées " are the convexities. Owing to their being usually filled with drift, the basins are less noticed than projecting rocks; but sometimes water alone occupies them, when we know them as lakes conspicuous for their clearness and purity. An example of a small mountain tarn of this kind is shown along with roches moutonnées of the Grimsel.

This leads us to a question still in discussion among geologists: to what extent has glacial erosion cut down the surface on which it has worked? On page 43 of our text, the fjords of the coast of British Columbia and Oregon are taken as reasonable evidence that continental glaciers once occupied that region; the fjords are held as most largely the result of glacial erosion, for the reasons given on p. 171. In opposition to this we may quote the following opinion as the result of many years' study by another observer. " Nowhere in any such region [as the Alps] denuded of its former icy covering, will it be found that the glacier has had any power to cut through an obstacle so as to form a channel with vertical, or nearly vertical sides, as water often does." † In this place we wish merely to note the difference of opinion without entering into the discussion. ‡

* In this expression is included, unless specially defined, all the wearing that takes place under a glacier, whether caused directly by pure ice, by stones frozen into the ice, or by subglacial streams. In the same way "stream erosion" includes the wasting by solution, the slight effect of pure water, and the abrasion by suspended particles.

† J. D. Whitney, Climatic Changes of Later Geological Times, p. 8.

‡ As an expression of personal opinion, the writer would say that even in the most heavily glaciated regions the present topography was well foreshadowed in preglacial times, and while glacial erosion must have rounded angular ridges and deepened pre-existent valleys and hollows, it has not originated such great features as fjords. Fjords alone cannot be taken as evidence of former glaciation. — W. M. D.

PLATE XVIII.

ROCHES MOUTONNÉES.

Some of the higher valleys of our Cordilleras retain traces of the local ice streams that once flowed through them. These traces are polished rounded or striated rocks, and morainal deposits; and of the former, those occurring in the valley of Roches Moutonnées Creek are so conspicuous as to give their name to the place. It is a moderate-sized valley in the Sahwatch Range of Colorado, leading from the mountain of the Holy Cross to the Eagle River, and in the Report of the Geological Survey of the Territories for 1873, the rocks are spoken of as giving the best examples of glaciated form in the region; they are striated in the direction of the valley. (See Plate XIX.)

Similarly worn rock-surface has been described from farther west by other explorers; in some instances the surface is so smooth as to yield but insecure footing, and the polish still so perfect as to give a good reflection.

So far as is known of the Cordilleras within the limits of the United States, the form of the rocks, the course of the striæ, and the direction of carrying of the transported boulders, all indicate that the glaciers moved from local centres of dispersion, coincident with the higher points of the district, and followed the valleys leading from them.

We may note in this connection the other agents by which rocks may be rounded so as to imitate the moutonnée form given by ice. Water may smooth an angular surface, but the resulting outline does not show the large curves produced by glacial action, and the effects are confined to narrow stream-beds. Weathering, due to atmospheric causes, will wear off the corners of an exposed ledge faster than the faces, so as in time to reduce it to a less angular form; but in this case the surface is somewhat loose from disintegration, and never firm and polished. (See Plate XXII.) Finally a concentric manner of jointing sometimes found in granitic rocks may produce smoothly convex forms, such as are seen in the neighborhood of the Yosemite Valley in California, where they have been mistaken for the effects of glaciation. By careful observation it is nearly always possible to discriminate between the results of glacial action and the other causes that produce a rounded form of rocks.

Roches Moutonnées [illegible] Colorado

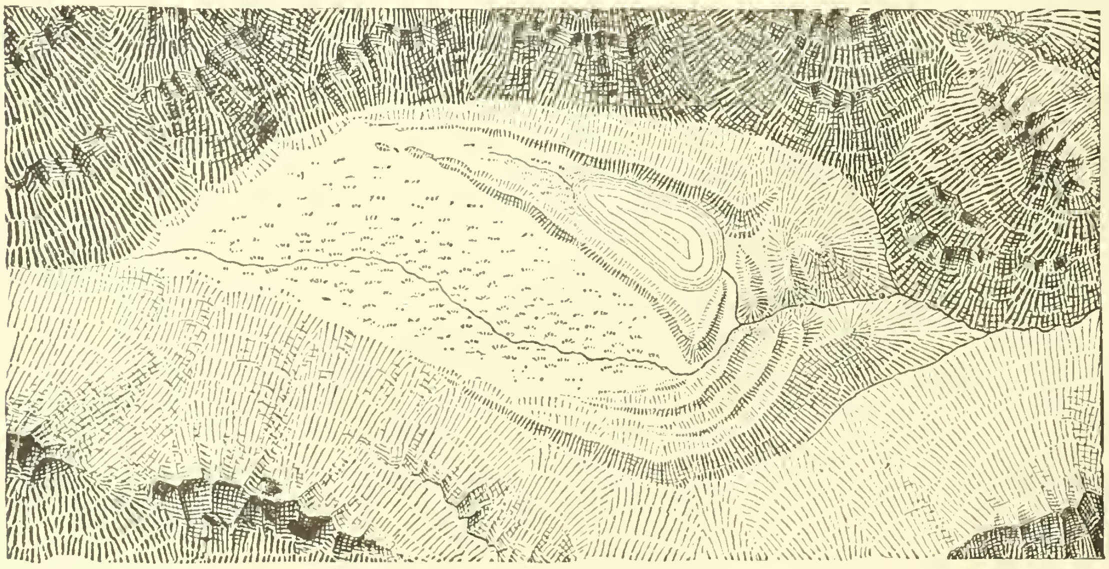
PLATE XIX.

ARKANSAS VALLEY MORAINES.

The detritus laid down by glaciers is generally accumulated in irregular deposits. The ground moraine, formed below the ice, only remains in hollows and the projecting rocks are left bare. This, however, does not apply to continental ice sheets, as their great ground moraine sometimes formed considerable hills, as is shown in Plate XXIV. Terminal moraines are built up unevenly, on account of the continual oscillation in the position of the ice front, and of the varying amount of material carried on the different parts of the ice surface. In the figure below, sketched from a ravine on Pike's Peak, Colorado, the several concentric ridges mark the limits of a small local glacier at successive halts during its retreat: the irregularity of their grouping is clearly seen. A pond occupied the central hollow within the ridges after it was vacated by the ice; but this is now converted into a marsh by the deposit of sediment from a stream that flows along the path of the old glacier. The pond that still remains between two morainal ridges has escaped complete filling because its supply streams are so small.

Lateral moraines are more simple and regular in form than any other glacial deposits. Variations in the size of a glacier are much less apparent at its sides than at its end, so that lateral moraines remain longer than terminals under nearly uniform conditions. Moreover, as the general advance of the glacier is parallel to its sides, an excess of detrital matter deposited at one point is carried along and distributed elsewhere, so as to form an even ridge, with a comparatively level summit line. These long mounds which stand in pairs in mountain valleys once occupied by ice streams, are peculiar to glaciers of the Swiss type: no such deposits were formed by the general ice sheets either in this country or in Europe, because they were nowhere confined by mountain walls. An approach to such ridges may be found in the lobe-shaped moraines, lately identified as such by Messrs. Chamberlain and Upham in Wisconsin and Minnesota; but these were accumulated in lines rather at right angles than parallel to the advance of the ice, and are therefore more properly considered as terminal than lateral deposits.

The lateral moraines of the Upper Arkansas Valley in Colorado, of which two are figured in Plate XIX., are remarkable for their size and distinctness. Their form seems to have lost little of its original sharpness, showing that the general surface erosion from rain and other weathering has not been considerable since the disappearance of the ice. In size, these long mounds might well receive the name of mountains, did they occur in a level country, although here they are quite overshadowed by greater masses. The examples here figured stand on either side of the cañon of Clear Creek, and project some distance beyond its mouth into the valley of the Arkansas. The terminal moraine that joins them is not conspicuous, but may be distinguished in the uneven surface of the foreground, where the creek cuts its way to the river.



Sketch of Terminal Moraines in a Ravine on Pike's Peak, Colorado.

91 MORAINES on CLEAR CREEK. VALLEY of the ARKANSAS. COLORADO.

PLATE XX.

GLACIAL STRIÆ.

Throughout the areas shown on Plate XXV. as formerly covered by continental glaciers, the rock surface, where not too much weathered, is almost universally scratched and scored as shown in the illustrations opposite. The scratches are of varying breadth and depth, from the finest perceptible up to channels in which one's arm might be laid; in length they may be several feet. They are very seldom other than straight, and within a given area are generally arranged in one or more parallel sets.

When attention was first directed to these markings, they were ascribed to floods from the north, which at that time were deemed competent to transport erratic boulders; but it was soon perceived that the scratches were more regular than could have been made by running water, and icebergs floating at a time of general submergence were suggested as efficient agents for their production. This in turn has been abandoned on learning that the scratches keep to a regular course for considerable distances, and sometimes even cross valleys and ridges obliquely. Floating bergs would ground only on ridges and peaks, not on deeply submerged valley bottoms; the markings produced by them would be far from regular; and besides these objections there is also the absence of any other evidence that the required amount of submergence ever took place.

Rock surfaces from which known glaciers, as those of Switzerland, have lately retreated, show precisely the same style of striations as those observed in Europe and North America in regions where the existence of glaciers had never been suspected. From these apparently insignificant surface markings, coupled with the occurrence of erratic boulders, there is derived ample evidence to prove the former existence of devastating ice sheets over regions now occupied by cities, fields, and forests.

In spite of the general acceptation of the theory of continental glaciation, and the frequency with which its phenomena are described in these days of modern popular science, very few persons know a glacial scratch by sight. Yet a surface marked by glacial striæ is so distinct from other eroded forms as to be very easy of recognition. The accompanying figures of glaciated limestone slabs from Chazy, N. Y., may serve as an introduction to out-door identification of these interesting markings.

While their direction is, in a large way, uniform over considerable districts, yet it is subject to slight deviations guided by the stronger topographical features of each region, and in the study of these there remains a large field open to amateur observation. Accurate measures of the course of striæ over some of our larger isolated New England mountains would be a very acceptable contribution to the study of glacial phenomena. Such observations may be made with a pocket-compass, of which the needle should be at least one and a quarter inches in length, and the arc graduated and read to at least two degrees. Care must be taken not to confound cracks or lines of stratification which enter the rock with the scratches which are merely superficial. When there is more than one prevalent direction for the striæ, as is often the case, all should be measured in accurate work, and, if possible, their order of making should be determined by examining the intersections. In recording the measures, it should be stated whether they are taken at places where the general trend would probably be affected by hill or valley; also, whether the record is of magnetic bearings, or of bearings corrected to the true north.

By mapping a large number of observations for all parts of the country, the general direction of glacial flow may be determined, and the centre of glacial dispersion located. This has been done by several geologists; most lately for Northeastern America by the Geological Survey of New Hampshire. The map is here reproduced by permission of Professor C. H. Hitchcock, Director of the Survey.

The distinctness of the marks of glacial erosion is dependent on several circumstances. The longer the time since the glacier has abandoned a region, the more completely will its effects disappear. The power of the rock surface to resist atmospheric decay is an important element: granites, quartzites, and slates generally weather slowly; limestones and loose sandstones more quickly. Sometimes a protecting sheet of drift preserves the rock from the accidents of time, so that where now uncovered by sea or stream erosion or by artificial excavation, a surface is exposed retaining all the finest glacial striæ. The same rock in an outcropping ledge may have long lost all its glaciated form.

The smooth, half-polished condition resulting from wearing down of a rock by fine material under the ice sheet sometimes seems to have a protective effect on its surface, as if it were too firm and even to allow weathering to begin its work. The same rock, when left unpolished, is more easily affected by decay.

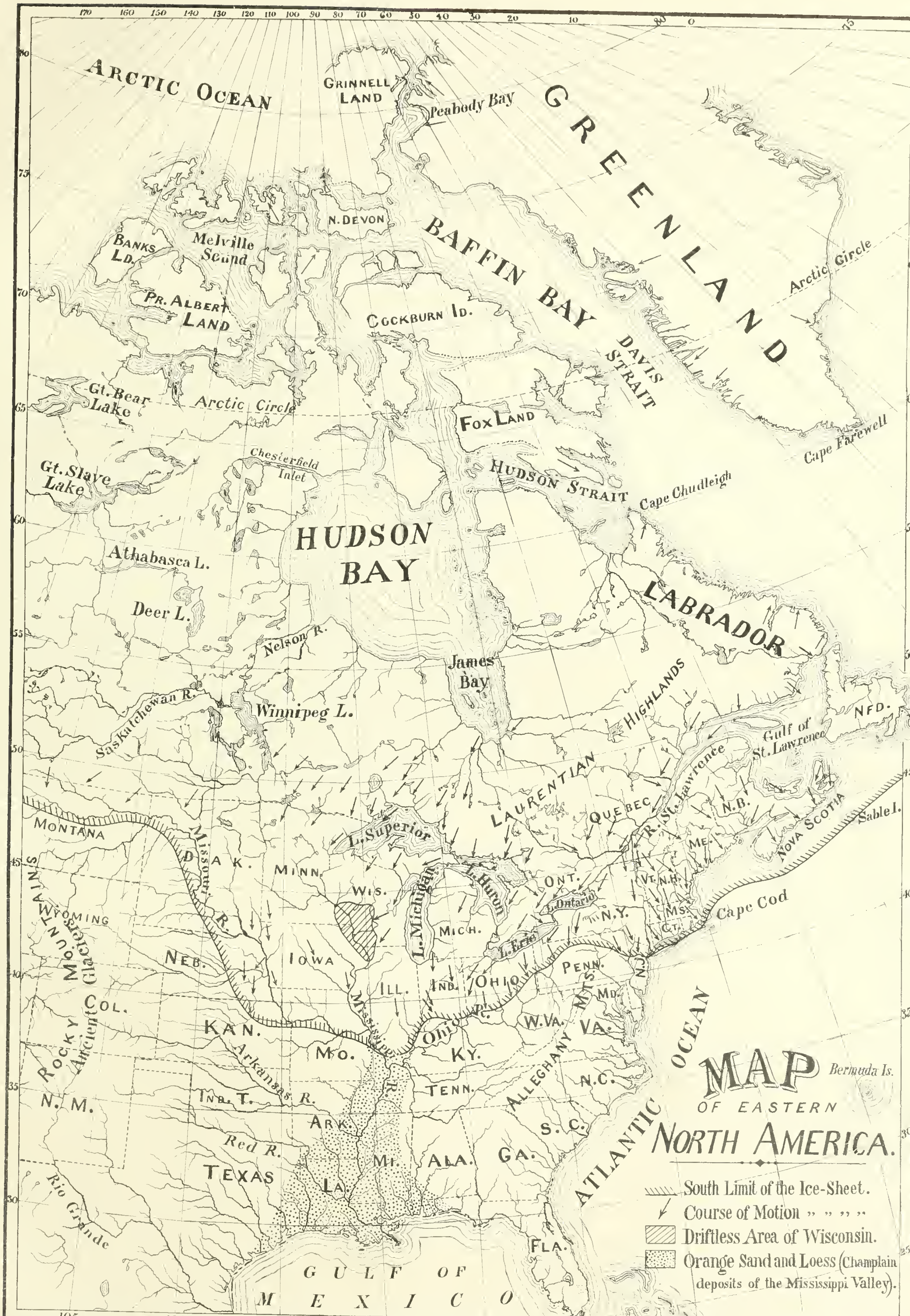


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PLATE XXI.

IMITATION OF GLACIAL SCRATCHES. — ICE AND WATER WORN PEBBLES.

There are some natural markings on rock surfaces, caused by land-slides or underground motion, that resemble glacial scratches, and which may have sometimes been mistaken for them; in careful observation there is no necessity for such confusion. Land-slides may score the rocks over which they pass, but these counterfeits are generally recognizable by the other effects of the accident. They are always so local that no large extent of country can be affected by them. The rubbing of one rock upon another, as in an underground movement, will frequently polish and striate the parts that bear the friction, and produce a surface known to miners as "slickenside." This is illustrated in two figures of Plate XXI. While in hand specimens this imitation might be sometimes confounded with the marks of glacial action, there is seldom any danger of mistake in field observations. "Slickensides" occur on divisional planes, exposed by quarrying, but not on the top of a ledge. They are essentially internal markings, and do not occur on the surface. Besides this difference in position, there is also a distinct difference in appearance, which is soon learned by the study of specimens.

Some further reference may be made here to the form of the scratches shown in the preceding plate. Their differences are to be ascribed to the varied form and hardness of the pebbles or grains of sand by which they were cut, and to the different pressures under which these acted. A sharp edge of flint held firmly in the ice would leave a smooth, fine line of considerable length; a hard, rough pebble would tear and break the rock, and leave a ragged furrow. The beginning and ending of certain scratches are included within the limits of the plate, the motion being from above downwards: the first marks the point where the cutting fragment was lowered so as to bear on the rock surface, the lowering being the result of the wearing down of other fragments or of a slight motion in the ice itself; or possibly the beginning of a furrow shows us where a grain of sand, before washed loosely about, was caught and set firmly in the moving mass, and carried forward with great force and under immense pressure. The end of a line may indicate either the wearing out or loosening of the cutting-tool, probably the latter as often as the former, for where the under surface of a glacier can be seen just after it has passed over a ledge, it as well as the rock is found furrowed by the pressure of the hard fragments that lay between the two surfaces. Curved scratches are occasionally found; even a succession of scallops has been observed, probably the result of the turning or lateral rolling of an irregular pebble as it was pushed forward.

The remaining figures represent ice and water worn stones, such as occur in unstratified and stratified drift. (See Plate XXIII.)

In the unstratified drift, fragments occur of greatly varied form, size, and composition. The larger boulders are derived from the harder or nearer ledges, and sometimes are of enormous size: in New Hampshire one is described as containing over 75,000 cubic feet, and weighing 6,000 tons, but it has been carried only a quarter of a mile from its source. In shape, the fragments that have been carried but a little way retain their angular, unworn outlines; those from a greater distance are rounded, but generally preserve something of their original faceted form, as if they had been more rubbed than rolled. The surface of the pebbles is generally scratched with lines that cross each other irregularly, thus indicating the irregular kneading motion of the detritus as it was shoved along under and in the ice.

The pebbles of stratified drift never attain the size of glacial boulders, unless floated to their new position on ice-rafts, as noted below. Heavy stones can only be washed along in strong currents, and therefore require streams of rapid flow for their transportation. They are carried only a short distance, and are deposited quite irregularly and often in oblique strata. Finer deposits are carried farther, and are laid down only in quiet water, as in sluggish streams, lakes, or bays, where they form a deposit of very uniform character. In our Western States there are broad areas of fine drift material, probably washed directly from the old glacier into a former extension of the Great Lakes, where it was quietly deposited in uniform layers. Stones and boulders of considerable size and sometimes of angular form are frequently found among the layers of these clays, and in this case, unlike the unstratified drift (Plate XXIII.), we have fragments that do not make a continuous series from finest to coarsest; only the extremes of the scale are represented. Hence there have been two independent methods employed in their transportation, namely, quietly flowing water, for the fine particles; and floating ice, sufficient to buoy up the larger masses. The ice probably came from the glacier front as icebergs, large or small. River or lake ice sometimes effects the same work. In stratified drift the pebbles are rounded, water-worn, and free from scratches; and even at a short distance from their source in a bank of boulder clay, they have lost the characteristic faceted form of a glaciated pebble: the sand grains are also worn like ground glass, while in boulder clay they are more angular.

PLATE XXII.

WEATHERED BOULDERS, CENTRAL INDIA.

The boulders scattered over the broad plain before us are examples of a peculiar effect of erosion that is sometimes wrongly interpreted. As seen here, they occur on a comparatively level surface, where water could not have had sufficient current to transport them; and therefore ice which, either in the form of bergs or glaciers, has been so frequently called on of late years to account for a variety of unexplained phenomena, is taken as the cause of their peculiar distribution. It is, however, unsafe to rely on the simple occurrence of numerous boulders as sufficient evidence of former glacial action, as will be seen by further description of the present case. In composition these fragments are like the rock on which they rest; therefore, no supposition involving transportation need be made. Their form is rounded, but the surface is loose in texture, not smooth, polished, or scratched, as it would be after glacial erosion; or angular, as in blocks carried on the back or within the mass of a moving ice sheet. Moreover, the largest boulders are, on the average, as well rounded as the small ones, thus indicating that rolling in a stream would not have produced their actual form. The proper explanation of their occurrence is that they once constituted ledges outcropping over the plain; that joints or cracks penetrating the ledges broke them into angular masses fitting closely together; and, finally, that atmospheric weathering, by acting fastest at the edges and on the corners, reduced the angular masses to rounded boulders. The gravel and sand resulting from such decomposition is washed or blown away, and leaves the nucleus of the blocks distinctly exposed. Great irregularity is not to be expected in the form of the jointed blocks, so that, in nearly every case, a spherical shape is approached as weathering progresses. In the group of blocks on the left there may still be noted a correspondence in size in the adjoining faces. At one time these all fitted closely together. They yet retain their relative positions, but the edges of the blocks are all weathered away.

It is rare to find so striking an example of this occurrence; and when seen on so large a scale, it might well deceive a casual or an unpractised observer, and lead him to believe that glaciers had acted in this region.

PLATE XXIII.

SECTIONS OF UNSTRATIFIED AND STRATIFIED DRIFT.

It is not uncommon to meet with persons whose education has familiarized them with the fact of the former occupation of northern countries by glaciers, yet who have never seen any of the numerous open proofs of the fact. Methods of field-work are seldom taught in schools or colleges, and it is a matter of difficulty to make an unaided beginning in this direction. To meet this difficulty, as well as to complete our series of illustrations, plates of roches moutonnées, of striated rock and pebbles, and of drift unstratified and stratified, are added to those representing actual glaciers.

The accompanying illustrations of drift are from photographs of a cut in a hill near Boston, on the Narrow-Gauge Railway from Boston to Lynn. Nearly every railroad in the Northern States has exposed similar sections; and when freshly cut, before atmospheric weathering breaks down their faces, it is seldom a matter of difficulty to understand their structure, and from that infer something as to their origin.

The first point to be observed is whether the gravel, sand, or clay, or the mixture of all of them, shows signs of arrangement in nearly horizontal layers, of finer and coarser particles, or whether fine and coarse materials are mixed indiscriminately, without indication of succession in strata. The first or stratified structure is evidence of water action, or occasionally of wind action; the second is the result of deposition by glaciers, without the aid of water. An imitation of this disorderly structure is produced in violent land-slides; but this is local and altogether exceptional, while within glaciated regions unstratified drift is of wide-spread occurrence.

A further examination of this kind of drift shows that it contains fragments from rocks often many miles to the north, though the greater part comes from nearer ledges. In New England, because of the difficulty in identifying the parent ledges, it is not always an easy matter to decide how far boulders and pebbles have been transported: on account of the enduring character of the rocks, the drift here is coarse and gravelly, with a smaller part of clay than is common elsewhere. In the Western States the frequency of fossiliferous rocks frequently simplifies the determination of the source of an erratic; in the same region the wasting of many soft argillaceous rocks yields a drift largely composed of clay. In all these sections there is a complete series in the size of fragments from smallest to largest, all commingled; and from this we may fairly infer that the transporting agent was of such great strength that it could disregard the variations in weight. The firmness of the boulder clay seems to be due, in some cases at least, to the great pressure of the mass of ice under which it was collected.

The section of stratified drift is from another part of the same pit, and indicates a hollow in the original surface of the boulder clay filled by washings from higher to lower parts of the surface; it is, therefore, necessarily arranged in layers, of which the lowest was deposited first and the highest last. In this arrangement each layer shows something of uniformity in the size of its particles, and the longer axes of the pebbles generally are placed horizontal. The materials in stratified drift have always been brought from some higher point, as their present position has been reached with the aid of running water; they are, therefore, not necessarily of northern origin, like the drift of our continental ice-sheet. When stratified drift is the product of stream erosion only, as in the Southern States, which are beyond the reach of glaciation, its pebbles come only from the rocks of the stream or river basin above its place of occurrence; but if derived from glacial deposits, as in the present illustration, it may have all their complexity of composition.

At the upper part of the first illustration there will be noticed an indistinct appearance of stratification: this probably corresponds to the "upper till," derived from fragments held in the ice and deposited as it melted, while the "lower till" was accumulated entirely beneath the glacier. The upper till contains fragments of rather more angular form than the lower, and is also less compact. The presence of water from the melting ice will account for its imperfect stratification. Layers of sand and gravel are not unfrequently found in the unstratified lower till; they owe their arrangement to the streams that must have flowed with irregular volume and in varying channels beneath the ice.

PLATE XXIV.

LENTICULAR HILLS NEAR BOSTON.

THESE views of lenticular hills were taken between the towns of Revere and Winthrop, a few miles northeast of Boston, on the sea-shore. The hills are not large examples of their class, but are very characteristic in outline. One is cut into for road material, and the section shows its unstratified structure.

In looking at hills and mountains with a view to classifying them according to origin and structure, we must take little account of size. The height to which their summits rise is of first importance in its effect on climate and political history, but of least when grouping them into varieties. A student of the earth's surface will soon learn to prize the examples of its forms from their perfection or rarity, more than from their size alone. Common species of great bulk may have less interest than smaller ones of comparative obscurity. Among the latter are to be included these rounded masses of drift known as lenticular hills. They occur in considerable number in New England, and probably elsewhere in regions of extensive glaciation, but their form and distribution have so lately received special attention that their extent cannot be accurately stated.

Most striking is their smoothness of outline: a very flat arch in the direction of length, as shown in the first view, with steeper fall on the sides, as in the second; their slope probably never exceeds thirty degrees. The base of the perfect specimens is a symmetrical oval, with axes in the proportion of two to three or two to four. In length they may reach a mile, and in height some exceed two hundred and fifty feet. The longer axis follows a determinate course, parallel to the later set of glacial striæ of their district, and independent of the form of the rocks beneath. They are composed of unstratified blue boulder-clay of firm and compact texture. The contained pebbles and boulders are subangular or rounded and strongly scratched. On the surface of the hills large boulders are of more frequent occurrence than below. For a certain depth, seldom exceeding fifteen feet, the clay is looser and yellow, owing to oxidation during or after their formation, as is explained on page 165. Lenticular hills are found at certain points on the coast of Massachusetts, and also at an elevation of fifteen hundred feet in New Hampshire. They are thickly distributed over certain districts; elsewhere they are altogether absent. No sufficient explanation has yet been given for their irregular occurrence.

On pages 61–63 of the text, the explanation suggested for these hills is that they are remnants of a more continuous layer of drift, deposited on the rock surface below, as the ice sheet of the glacial period melted away; that the present form of those about Boston is due to tidal erosion, which cut away most of the drift layer, and to atmospheric weathering, which rounded the remnants to their present graceful form.

Another explanation has been given by Mr. Warren Upham.* He supposes that the lenticular hills were collected beneath the glacial sheet, and moulded closely to their present form before the disappearance of the ice; that the changes due to post glacial erosion are insignificant, excepting in cases of sea-cliff cutting, as in our first view; and that only a few feet of surface clays ("upper till"), yellow and of looser texture, together with the numerous surface boulders, are derived from the melting of the ice.

In comparing these two explanations, we may note, first, that the regular trend of the hills is more likely due to the motion of the glaciers with which it agrees, than to the accidental direction of tidal or other erosion, or than to the irregular form of the supporting "pedestal"; second, that the form of the hills might well be that of least resistance to an ice sheet moving over them in the direction of their length, but is not the shape given by postglacial erosion elsewhere. Tidal erosion has been possible only near the shore, and has never reached the inland hills; stream erosion has not generally acted on the drift excepting as small rain rivulets, and these have not had time or strength, since the disappearance of the ice, to effect nearly so great erosion and transportation as must be claimed for them under the first explanation. This is abundantly proven by kames, which preserve to the present day the forms given them at the retreat of the great glacier.

The only cases where streams have effected considerable postglacial erosion is where they are collected into rivers of rapid current, and it cannot be supposed that streams of such consequence have flowed either at the same time or in succession through the valleys that now separate the lenticular hills. Moreover, the form given to a sheet of drift by tidal, stream or subaerial erosion would not be an arched hill, but more like a table or "mesa," as is frequently seen in New England and elsewhere. Erosion therefore seems insufficient to produce the result ascribed to it under the first explanation, and we accept, in preference, the hypothesis of Mr. Upham.

The line between the upper or yellow and lower or blue clays does not coincide with the division between the upper and lower till, since the yellow color, due to weathering, frequently extends beyond pebbles that are scratched as distinctly as any in the blue clay below. A difference of structure, therefore, and not of color, must be taken as separating the drift accumulated below the ice from that deposited during the melting. The upper till is of looser texture, shows signs of stratification, and contains pebbles and boulders less scratched and more angular than those of the lower till. The difficulty of showing why the drift should accumulate at certain points beneath the ice, as required by the second explanation, is more than matched by the impossibility of accounting for the regular trend and form of the hills by the first; and the statement that the hills generally rest on pedestals and owe their preservation to this position, is embarrassed by so many exceptions that it cannot be regarded as essential to their description.

* Proceedings of the Boston Society of Natural History, Vol. XX. p. 220.

PLATE XXV.

THE PAST AND PRESENT DISTRIBUTION OF GLACIERS.

The small scale of the maps, made necessary by the size of our pages, prevents their showing the detailed distribution of existing glaciers; this has, however, the advantage of bringing before us at a glance the two regions of the world that experienced heavy and broadly extended glaciation in Post-Tertiary times. After reading of continental glaciers, one is surprised to find how small a part of the continents they covered, even during their greatest development. The scattered mountain glaciers south of the great northern ice sheets were quite insignificant in area compared to the remaining land surface. The mountains of Switzerland probably furnished the largest of these.

Chapters III. and IV. give, for our purpose, a sufficiently detailed geographical description of the glaciers of present and past times: we need here only refer to certain parts of the map that need further explanation. The more important authorities consulted will be found under the bibliography of the subject, on pages 177–191.

For Europe, observations are sufficiently exact to leave little room for doubt as to what regions should be shaded. Curved lines within this area show the general direction of glacial striæ outward from Norway and Scotland. South and southeast of the Baltic Sea it is supposed that a general submergence allowed icebergs to float over Northern Germany as far as the southernmost extension of northern erratics.

In Northeastern America the southern termination of the ice sheet has been fairly well determined; and also a line of moraines marking a temporary halt after a short retreat; but the far North and Northwest is little known. Explorations in that direction have been generally made by men little acquainted with the effects of glaciation, and their reports mostly contain very little information on the subject. The presence of numerous and irregular lakes, and the sand-hills and boulders frequently reported, make it probable that the old ice sheet covered all region east of the line from Lake Winnipeg up to the mouth of Mackenzie River. Alaska is said by Dall not to have been glaciated; but we have yet to learn the conditions of the far northeastern part. The centre of dispersion of this great glacial system seems to be east of Hudson's Bay; its connection with Greenland on the northeast is inferred by some, but as yet is not proven.

The Coast Ranges of British Columbia were heavily glaciated, but on all the rest of our Cordilleras, so far as observed, there were only local groups of glaciers which did not coalesce in a general sheet, as in the east. Their distribution is still imperfectly known, and can only be roughly shown on our map.

The few scattered glaciers of the Andes north of Patagonia are at the present time unimportant, and are not known to have had a significant extension in earlier times. South of Chili they once assumed considerable proportions on the west coast, and in some valleys still reach the sea; the eastern side of the chain is practically unknown. The southern island of New Zealand was heavily glaciated. Asia, as far as explored, shows the ice period as nothing more than a greater development of existing glaciers. Part of the southern slope of the Himalaya is fairly well known; in no cases did the glaciers extend beyond the mountain valleys to the plains. Elsewhere information is very meagre, but always points to the same result. The so-called "polar ice-cap" is not yet shown to have reached to the northern coast of Siberia; all that barren shore shows no marks of glaciation. Indeed, the "polar ice-cap" is largely hypothetical, as may be seen from a glance at our map, on which the glaciated regions are certainly represented in all the extension that can fairly be claimed for them. We should be cautious in attributing too much displacement of the ocean to the attraction of the glacial sheets.

The existing glaciers are the shrunken remnants of larger predecessors. For some little known regions this cannot be taken as fully proved, but from analogy it is extremely probable. On antarctic lands there has been no exploration; they have only been sighted from ship-board. They are snow-covered, and glaciers extend to their shores; but of the region beyond, toward the pole, nothing is known. With one exception, all the expeditions to these distant seas were made before the study of glaciers had received special attention, and the only observations of much value to us were made by Ross, who saw the great cliffs of an ice sheet extending into the sea, with a front over four hundred miles long, and one hundred and fifty to three hundred feet high. This type of shore must have had its parallel off our own coasts and those of Norway and Scotland during the glacial period.

The present condition of Greenland is a matter of discussion. It is known only along parts of its coast and a short way inland at a few points. An ice front is found at varying distances from the shore on the west,

extending in an irregular but practically continuous line, whence the ice rises unevenly eastward. No explorers have yet reached its culminating ridge, unless in the south where the land is narrowest. The eastern coast is less known; but where recently approached the ice front seems less continuous and more irregular than on the west. Some suppose that all the interior is occupied by ice; others suppose that the glaciers are heaviest on the western coast range, less so on the eastern, and least extensive or possibly absent in the interior. In the absence of exploration, it is left half-shaded on the map. The archipelago west of Greenland is described as surprisingly free from glaciers, but in most Arctic narratives, especially the older ones, observations on this subject are very scanty and unsatisfactory.

The conventional profiles give the more important mountains, placed in order of latitude, and showing the altitude of their summits, snow-line, and lowest glacier. They are based on a table by Berghaus,* to which a few additions have been made from other sources. Their names are given in the following list: —

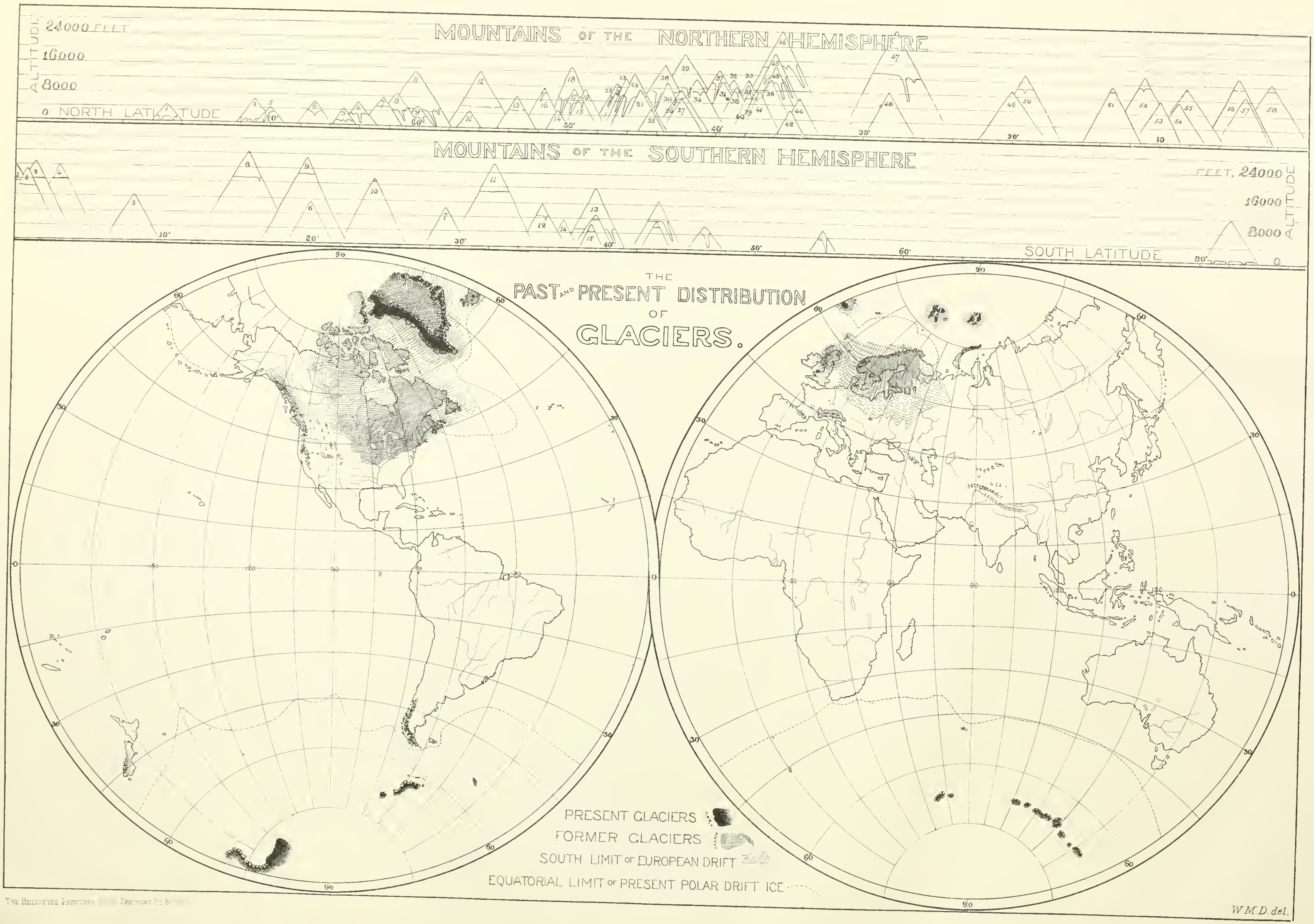
MOUNTAINS OF THE NORTHERN HEMISPHERE.

No. on Profile.	Country or Range.	Mountain.
1.	Spitzbergen	Horn Sund Pik.
2.	Jan Mayen	Bären Berg.
3.	Iceland	Hecla.
4.	"	Oraefa Jökull.
5.	Norway	Bensjordtinden.
6.	"	Sulitelma.
7.	"	Snehaetten.
8.	"	Galdhöppig.
9.	"	Near Tokheim.
10.	Scotland	Ben Nevis.
11.	Alaska	St. Elias.
12.	Kamtschatka	Kliutschewsker Volcano.
13.	Aleutian Islands . . .	Unnamed.
14.	Silesia	Schneekoppe.
15.	Carpathians	Tatra.
16.	Siberia (Altai Mts.) . .	Munku Sardik.
17.	" " . .	Bjelucha.
18.	Rocky Mts., B. A. . .	Mt. Hooker.
19.	Cascade Range . . .	Mt. Baker.
20.	" " . . .	Mt. Rainier.
21.	" " . . .	Mt. Hood.
22.	Alps	Wildspitz.
23.	"	Monte Rosa.
24.	"	Mont Blanc.
25.	White Mountains . . .	Mt. Washington.
26.	Pyrenees	Pic Néthou.
27.	Apennines	Mte. Corno.
28.	Caucasus	Elbrus.
29.	Thian Shan	Khan Tengri.
30.	Rocky Mts. (Wyoming),	Fremont's Peak.
31.	" " (Colorado) .	Gray's Peak.
32.	" " " .	Mt. Harvard.
33.	" " " .	Blanca Peak.
34.	Sierra Nevada (Cal.) .	Mt. Shasta.
35.	" " " .	Mt. Dana.
36.	" " " .	Mt. Whitney.
37.	Asia Minor	Ararat.
38.	" "	Erjish.
39.	" "	Taurus.
40.	Sicily	Ætna.
41.	Sierra Nevada (Spain) .	Mulahacem.
42.	North Carolina . . .	Mt. Mitchell.
43.	Persia	Demavend.
44.	Syria	Dhor el Chotib.
45.	Kün Lün	Unnamed.
46.	Karakoram	"K2."
47.	Himalaya	Gaurisankar (Mt. Everest).
48.	Canary Islands	Teneriffe.
49.	Sandwich Islands . . .	Mauna Loa.
50.	Mexico	Orizaba.
51.	Abyssinia	Abba Jared.
52.	Columbia	Horqueta.
53.	Costa Rica	Irazu.
54.	Panama	Chiriqui.
55.	Venezuela	Sierra de Santa Marta.
56.	Andes, Columbia . . .	Tolima.
57.	" " . . .	Puracé.
58.	Guinea	Cameroons.

MOUNTAINS OF THE SOUTHERN HEMISPHERE.

No. on Profile.	Country or Range.	Mountain.
1.	Andes, Ecuador . . .	Cayembe.
2.	" " . . .	Cotopaxi.
3.	" " . . .	Chimborazo.
4.	E. Africa	Kilimanjaro.
5.	Java	Semeroe.
6.	Madagascar	Unnamed.
7.	S. Africa	Drakenberg.
8.	Andes, Bolivia	Sorata, or Illampu.
9.	" Peru	Sahama.
10.	" Chili	Llullayaco.
11.	" "	Aconcagua.
12.	Andes, Chili	Cerro Florido.
13.	" "	Villarica.
14.	Australia	Mt. Hotham.
15.	New Zealand	Unnamed.
16.	" "	Ruapehu.
17.	" "	Mt. Cook.
18.	Andes, Patagonia . . .	Corcobado.
19.	" " . . .	Unnamed.
20.	" Tierra del Fuego	Mt. Sarmiento.
21.	Antarctic Land	Mt. Erebus.

* Höhentafel von 100 bekannteren Gebirgsgruppen der Erde, von Herm. in Berghaus, in Behm's Geographisches Jahrbuch, 1866, p. 256.



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